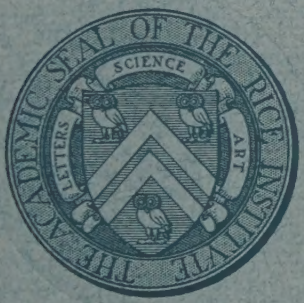
THE RICE INSTITUTE PAMPHLET

Vol. XVIII April, 1931 No. 2



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A university of liberal and technical learning founded by William Marsh Rice in the City of Houston, Texas, and dedicated by him to the advancement of Letters, Science, and Art

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SIDEREAL EXPLORATIONS[1]

INTRODUCTORY STATEMENT

IN the following pages I present an account of a series of explorations. The quests are cosmographic rather than geographic, and therefore differ widely from terrestrial expeditions in equipment and aim; but there are some features in common—the optimistic accounts of partial successes, the complaints about obstacles, weather, and insufficient equipment, and the suggestions of still more fascinating regions down mysterious by-roads, or out beyond the horizon.

The report is concerned with the progress, throughout eight regions, of researches which, considered in sequence, exhibit our expanding knowledge of the sidereal universe. The account concerns some of the plans for the future as well as current work, and deals almost wholly with observations and studies that are carried on at the Harvard Observatory at Cambridge and at its southern station, formerly in South America, now at Bloemfontein, South Africa.

The general line of attack on problems of galactic measurement and analysis was outlined many years ago; but only recently have we been able to proceed effectively with explorations into all the territories included in the general program. The survey extends from the nearest stars of the Solar Neighborhood to the remotest nebulous patches that we can photograph in our telescopic surveys of the

[1]Based on lectures given at the Rice Institute, March 9, 10, and 11, 1931, by Harlow Shapley, Ph.D., Director of the Harvard College Observatory and Professor of Astronomy in Harvard University.

Metagalaxy. Progress can be claimed in all territories, but not conquest. Our acquisitions are small compared with the unfolding unknown. Some parts of the program may be satisfactorily completed in ten or twenty years; other phases extend indefinite decades into the future. Meanwhile we shall approach understanding through sampling processes and through reasonable extrapolation, leaving to future astronomers the pursuit of detailed studies in fields now but provisionally explored.

Limitations of space will prevent full discussion of the work in all eight regions. Previous studies are summarized very briefly, and current investigations are only partially reported; but throughout the discussion many results heretofore unpublished are given in text and diagram.

The eight territories, in order of distance, are the following:

1. *The Solar Neighborhood,* out to a distance of fifty light years, explored chiefly through studies of the motions of nearby stars.

2. *The Sphere of Lucid Stars,* extending five hundred light years from the solar system, and studied by us mainly through that joint agency of photometry and spectroscopy—the method of spectroscopic parallax.

3. *The Local System,* out to five thousand light years or so, investigated statistically, for the most part, on the basis of the spectral classifications, magnitudes, and positions of tens of thousands of faint stars; but also explored by means of spectroscopic parallaxes, star counts, and studies of variable stars and galactic clusters.

4. *The Milky Way,* with a radius in excess of fifty thousand light years, and yielding its secrets very slowly to our probing by means of variable stars.

5. *The System of Globular Clusters,* coextensive with the

Milky Way itself, or perhaps larger, and explored mainly through photometry of the giant and supergiant stars, variable and invariable, which are congregated into the hundred known globular systems.

6. *The Clouds of Magellan,* almost a hundred thousand light years distant, and yet the nearest of all external galaxies and the most easily studied, whether photometrically, spectroscopically, astrometrically, or statistically.

7. *The Supergalaxies,* varying in distance from one million to a hundred million light years and more, and in brightness from naked-eye visibility to the ultimate of telescopic faintness, composed of many unit galaxies, sometimes of hundreds or even thousands—measured with increasing difficulty as the distances increase and the light grows fainter.

8. *The Metagalaxy,* extending beyond the limits of the greatest existing telescopic power, composed of millions of individual and clustered galaxies, including also the Magellanic Clouds, the globular clusters, our Milky Way, and the Local System. The faint external galaxies, which constitute the body of the Metagalaxy, are investigated, in our explorations, for brightness, position, form, size, distance, and velocity. It is in this extensive metagalactic realm that we find some evidence of a literally expanding universe, as remarkable as the expanding knowledge of the sidereal world.

To several members of the Observatory staff I am indebted for assistance in presenting this interim report on our joint researches in galactic measurements and structure. The details of our investigations are published principally in the Bulletins, Circulars, and Annals of the Harvard Observatory.

April 15, 1931

I

IN THE SOLAR NEIGHBORHOOD

CURRENT custom leads us to define the galactic system as the sidereal organization that includes all known stars and nebulae, bright and faint, except those in the globular clusters and in the external galaxies. The galactic system is, therefore, essentially the whole stellar system—it includes the naked-eye stars, the remote Milky Way clouds, the intervening fields of stars and nebulae. Hence the explorations in this system, which contains our first four territories, extend over a wide range of distance and employ several techniques.

Following the outline given in the introduction, we shall go into the various territories, travelling from the Earth outward, and deal with each in turn, recognizing of course that the regions overlap somewhat and that the same methods of exploration and analysis may appear in several different fields.

We begin with the problem of hunting down the Sun's nearest neighbors; but before we get too far from Earth let us refer briefly to three new explorations inside the solar system.

a. Meteors. Within a hundred miles of the Earth's surface there is a continual astronomical display that has deeper significance in our understanding of cosmic matters than has any individual planet, star, or nebula. The shooting star is allied, in a manner too little known, with comets, dark nebulae, and the wandering population of interstellar

space, and throws light on the terrestrial atmosphere and on the mystery of planetary origin. We shall also know more concerning the mass of the universe, the transparency of space, and the evolution and ages of stars when we have added to our fragmentary knowledge of meteors. To be sure, prolonged and informative investigations of meteors have been made in the past, but the field is still largely unexplored; the professional has too often left the subject to the amateur whose equipment and time are insufficient for the work.

Realizing the opportunities in the study of meteors, we have slowly but persistently developed this work at the Harvard Observatory. Nearly ten years ago a search for meteor trails on photographs was begun. Approximately one hundred thousand plates in the Harvard collection have now been examined, and a total of 386 meteor trails discovered.

The study of the meteor photographs goes forward steadily under the supervision of Dr. Fisher. It involves considerations of such factors as brightness, altitude, radiants, multiple trails, and interruptions of trails through rotation of the meteors. The meteors have in general been photographed accidentally in the course of routine stellar photography; their rapid motions permit only the brightest to be recorded on the plates. Practically, we get only the relatively slow-moving and exceedingly bright fireballs, and we have no photographic record whatever of the common shooting stars that can be seen by dozens on any clear moonless night. Further development of photographic technique for the specific purpose of photographing faint meteors is an immediate and difficult problem.

Because the photographic methods are still ineffective except for the brightest objects, the quantitative investigation

of meteors depends on the eye. We have here a department of astronomy—one of the few—in which visual observations are still superior to photographic records.

It would be premature to discuss in detail the current program for the systematic visual observation of meteors. It will suffice to say that it involves special photographic work in addition to the more general visual program. A well-equipped observing expedition to a specially favorable locality in the Southwest is a major part of the plan. Emphasis will be placed on the casual meteor rather than on the meteoric showers. Simultaneous observations from stations separated by twenty or thirty miles will provide information on meteor heights. Special devices will be tried for the determination of meteoric speeds. Telescopic observations will supplement the naked-eye work in providing information on the frequency of faint meteors and will contribute ultimately to our knowledge of the dispersions in size and the distribution in height. We have yet to learn whether the majority of shooting stars are members of our solar system or are drifting representatives of the sparse population of interstellar space.

b. Eros. At the moment of writing (March, 1931) the asteroid Eros is the Earth's nearest companion, except the obvious Moon and perhaps some undiscovered comet. Thirty years ago the variation of the light of Eros came under study with Harvard photometers, first by Professor Wendell and later by Professor Bailey. The periodic variations in the brightness of this small body, which travels a very eccentric orbit, suggested long ago an irregular form, or perhaps a spotted surface. That the variation at that time was vigorous and easily measurable for a few months and later was nearly or quite undiscernible is well known; a completely satisfactory explanation of this peculiarity is not yet at hand.

Miss Harwood's subsequent photometric studies of Eros at the Nantucket and Harvard observatories have also shown varying degrees of variability in its light. During the present most favorable opposition Mr. Campbell has followed the asteroid photometrically throughout several months. At first the variation was more than a magnitude and the period a little more than two and a half hours. Then throughout January, without a change of period, came a rapid decrease in the amplitude of variation to less than one half its earlier value.

One conclusion of Mr. Campbell's study is that the period of variation is the same now as it was thirty years ago—it has not changed a measurable fraction of a second in thirty years. Since the variation is probably associated with the rotation of an elliptical or binary body (the elongation of Eros has recently been directly observed by van den Bos and Finsen at the Union Observatory, Johannesburg and by Nakamura at Kyoto), the "day" of this twenty-mile minor planet is double that of the period of light variation. Mr. Campbell finds this double period to be

$$5^h\ 16^m\ 12^s.94$$

c. The ecliptic patrol. Moving in more nearly circular orbits than that of Eros, and at much greater distances from the Earth, is the main body of asteroids. More than a thousand are definitely recorded, and additional thousands will undoubtedly be revealed by explorations of the region between the orbits of Mars and Jupiter. The general study of asteroids is not a part of the Harvard program; but to provide for the future needs of astronomers in checking the motions of known and unknown asteroids, a systematic patrol of regions along the ecliptic has recently been initiated at the Cambridge station. Two photographic tele-

scopes take care of this program. One is the 12-inch Metcalf refractor; the other a 3-inch Ross-Lundin lens attached to the mounting of the 12-inch telescope. The 3-inch covers a field several times as extensive as that effectively photographed with the larger instrument. The program is so designed that the zodiacal belt is covered three times a year, each time with widely overlapping plates. Stars to the fifteenth magnitude are recorded; but because of their motions, the asteroidal images are elongated and the magnitude limits are appreciably brighter.

With their useful distribution throughout a wide range of galactic latitude, the plates of the ecliptic patrol should also provide in the course of a few years valuable material for a systematic study of certain types of variable stars.

Proceeding to the Sun's neighbors, we note that the brighter stars are the nearer stars. This plain statement seems to border on the obvious. It is true, however, only when a great many stars and their average distances are considered. Some of the bright stars are near; many are not. Actually, the majority of the *nearest* stars are invisible to unaided eyes; and some of the brightest naked-eye stars are beyond the range of trigonometric measurement.

The reason why brightness is a poor criterion of distance lies in the great variety found in the intrinsic luminosities of stars. Some stars are thousands of times as bright as the Sun; others less than a thousandth as luminous. The weakly shining stars, which may actually be very numerous throughout space, naturally can be known to us, even telescopically, only if they are very near. A star a thousand times as bright as the Sun, however, can be seen with the unaided eye at a distance of fifteen hundred light years.

The problem of finding the solar neighbors is therefore

not a search among the few thousand naked-eye stars. The exploration must clearly lead down into the fainter magnitudes. Our task is to pick out in some manner from the millions of stars shown on photographic plates those objects which are in the immediate vicinity of the Sun. We have seen that we cannot safely pick them out by brightness. A more adequate tool is found to be the angular motion of the stars across the sky. Individual stars, to be sure, differ somewhat in linear speed, but still the angular displacement is a better indicator of distance than is the observed brightness. Once the large angular motion of a star is discovered, the nearness can not only be confirmed but actually be measured through the usual trigonometric method of measuring stellar parallax.

The angular motion on the surface of the sky observed for individual stars may be attributed in part to the star's own motion, in part to a reflection of the annual motion of the observer around the Sun, in part to a reflection of the motion of the solar system through space. For all these sources of angular motion, the nearer the star the greater the displacement. Again, however, though in lesser degree, we are confronted with the same difficulty that made observed brightness a weak criterion. These displacements would all be excellent indicators of distance, except for two reasons: (1) the considerable dispersion in the real motion of the stars; (2) the smallness of the angular motion of all but a few hundred nearby stars, with resulting uncertainties in their measurement.

The data assembled in Table I show the proper motions of the sixteen nearest stars that are now known. The magnitudes range from -1.6 to $+13.5$, and correspond to a ratio of a million to one in brightness; but the angular motions show a range only from one to ten.

The practical search for the Sun's neighbors is simply the problem of comparing duplicate early and recent plates made with a telescope of sufficient focal length to show the relative displacements of nearby stars. Such a comparison discloses the fact that in the time elapsing between the dates of the two plates, certain stars have moved noticeably in the field. The instrument used by the Harvard Observatory for this purpose is the Bruce photographic doublet of twenty four inches aperture, mounted for many years at Arequipa, Peru, and now at the Harvard station in South Africa; for more than thirty years it has been photographing southern stars. Hundreds of the photographs, for which the exposures range from fifty minutes to four hours and more, were made before 1900. A program of repeating, under comparable conditions, the older photographs made at Arequipa was taken up systematically a few years ago, and is carried forward under the supervision of Dr. Paraskevopoulos at the Boyden Station near Bloemfontein.

Before this systematic program was inaugurated there had been made, for one reason and another, many duplicate photographs on the old regions, with intervals in excess of twenty five years. Dr. Luyten's examination of many of these pairs of plates has resulted in the discovery of several hundred stars with annual motions in excess of 0″.1. Some of these, to be sure, may be high velocity stars more than a hundred light years distant; but the majority are nearby stars of normal velocity. Only those of conspicuously large angular motion, however, are likely to be in the immediate solar neighborhood.

It will be many years before the whole southern sky is systematically covered a second time with photographs suitable for the study of large angular motions. Within the past two years three hundred and fifty plates have been

Table I

Sixteen Stars Nearer Than Five Parsecs*

Name	R.A. 1900		Dec. 1900		Visual Magnitude	Spectrum	Annual Proper Motion	Parallax	Distance in Light Years	Absolute Visual Magnitude	Luminosity in Terms of the Sun
	h	*m*	°	′			″	″			
Proxima Centauri	14	22.9	−62	2	11.	dM	3.76	0.786	4.15	+15.5	0.000055
α Centauri A	14	32.8	−60	25	0.3	G0	3.68	.758	4.30	+ 4.7	1.15
α Centauri B	14	32.8	−60	25	1.7	K5	3.68	.758	4.30	+ 6.1	0.32
Barnard's Star	17	52.9	+ 4	28	9.7	dM3	10.30	.542	6.01	+13.4	0.00038
Wolf 359	10	51.6	+ 7	36	13.5	dM4e	4.84	.407	8.0	+16.5	0.000022
Lalande 21185	10	57.9	+36	38	7.6	dM2	4.77	.403	8.1	+10.6	0.0050
Sirius A	6	40.7	−16	35	−1.6	A0	1.32	.363	9.0	+ 1.2	29.
Sirius B	6	40.7	−16	35	8.4	dA7	1.32	.363	9.0	+11.2	0.0029
B.D.−12°4523	16	24.4	−12	24	9.5	dM5	1.24	.351	9.3	+12.2	0.0011
Innes' Star	11	12.0	−57	2	12.	.....	2.69	.340	9.6	+14.7	0.00011
B. D.−7°4003	15	14.3	− 7	21	9.2	dM5	1.33	.331	9.8	+11.8	0.0017
Kapteyn's Star	5	7.7	−44	59	9.2	dK2	8.70	.320	10.2	+11.7	0.0018
τ Ceti	1	39.4	−16	28	3.6	K0	1.92	.319	10.2	+ 6.1	0.32
ε Eridani	3	28.2	− 9	48	3.8	K0	0.97	.305	10.7	+ 6.2	0.29
Procyon A	7	34.1	+ 5	29	0.5	F5	1.24	.304	10.7	+ 2.9	6.0
Procyon B	7	34.1	+ 5	29	13.	.....	1.24	.304	10.7	+15.4	0.00006

*P. van de Kamp, *List of Stars Nearer than Five Parsecs*, Pop. Astr., **38**, 1, 1930.

made on this program, chiefly by Dr. Luyten. The survey of the solar neighborhood from this standpoint will not be completed until the Bruce telescope, or some similar instrument, has provided material for the north such as that rapidly accumulating in the Harvard plate collection for southern stars.

At present there are more than sixty stars known to be within twenty five light years of the Sun. On the basis of simple theory we can predict, not too securely, how many more are likely to be found. It is important, however, to find them, and to measure their distances accurately, to study their spectra, to note any abnormalities of color, and of course to determine with the spectroscope, if possible, the component of the motion in the line of sight.

When we have these data complete, and thus know the relative number of giants, normal stars, dwarfs, and subdwarfs in the solar neighborhood, we shall be well on our way toward a general knowledge of the total numbers of stars, and of the significance in stellar evolution of their distribution in luminosity and mass; for the solar neighborhood is the only place where we can effectively study dwarf and subdwarf stars. We have abundant samples of areas on the surface of the sky, and we explore them intensively, but the solar neighborhood is the only adequate sample of a volume of sidereal space. Its exploration is a long and painstaking task for the observers of trigonometric parallax, and especially for the investigators of angular motions of the faint stars.

II

THE SPHERE OF LUCID STARS

TO supplement the results on the distances of the stars obtained by observers of trigonometric parallax, the method of spectroscopic parallax was developed by Adams and Kohlschutter some fifteen years ago. The method is primarily photometric, since the derivation of a star's distance in parsecs, $\log d = 0.2\ (m - M) + 1$, depends as much on the photometric measurement of the apparent magnitude m as on the derivation of the absolute magnitude M, and the absolute magnitude also is determined from photometric estimates of the intensities of lines and bands in the stellar spectra. The progress of the spectroscopic parallax method has been somewhat disappointing. The difficulties are largely observational, but they are partly dependent on uncertainties in the correlation of line intensities with absolute magnitudes for the various spectral classes of stars.

At the Mount Wilson and Harvard observatories considerable attention has been given to the search for new criteria of absolute magnitude in stellar spectra. At the Dominion Astrophysical Observatory in Victoria, Harper and Young have investigated, extended, and applied the original Mount Wilson criteria. Lindblad, in Stockholm, has made use of the cyanogen absorption band in the effort to find workable indicators of the real luminosities of stars. Also at the Norman Lockyer Observatory, and at Arcetri and elsewhere, the absolute magnitudes and distances of early type stars have been estimated.

Notwithstanding the extensive work in this field, much remains to be done in a fundamental way. It appears that there is less need than formerly suspected of spectroscopic criteria for the absolute luminosities of stars of the late spectral classes, because the dispersion in the actual luminosities is not so great but that, for the present at least, rough criteria are sufficient to distinguish supergiants, giants, and dwarfs. Greater difficulty is encountered in estimating the absolute luminosities directly from the spectra of the hotter stars, Classes B, A, and F.

In one contribution toward the study of the distances of stars bright enough to permit spectroscopic analysis, the Harvard Observatory has for several years been photographing individual stars in the southern hemisphere, particularly with the 13-inch Boyden telescope and objective prism. Supplementing the general collection of spectrograms, a considerable amount of special material has thus been accumulated, which can be evaluated when further study of the criteria of absolute magnitude makes possible its use. Current researches on the criteria by Dr. Öpik, Miss Anger, and others concern not only relative line intensities but line contours and the distribution of light intensity throughout the spectra. What we need is to discover new indicators such that they will not only open up the region of the naked-eye stars but penetrate to stars a few magnitudes fainter. The aim of this inquiry is an understanding of the distribution of objects which lie too inconveniently remote for ordinary trigonometric survey, but sufficiently close to the solar neighborhood to be, because of their proximity, of high importance in many astronomical problems.

III

THE LOCAL SYSTEM AND THE HENRY DRAPER EXTENSION

FOR more than a century astronomers have been systematically examining the distribution of both naked-eye and telescopic stars, recording their numbers in different parts of the sky, and determining their increasing frequency with decreasing apparent brightness. Important and laborious catalogues have been compiled of the radial velocities, the proper motions, the magnitudes, the positions, and the spectra of thousands of stars. Although it was realized that the stars extend in great numbers beyond the limits of available telescopic power, it was generally felt a generation ago that current studies were dealing with a very considerable part of the stellar system. In recent years, however, we have come to the realization that our catalogues pertain to a localized bit of the sidereal universe and that the major part of even our own Milky Way system is comprised of stars fainter than the tenth magnitude, and is more than ten times as remote as the average catalogue star.

Analyses of the data of our catalogues, especially the study of positions, numbers, and spectra, long ago showed structural detail in the arrangement of the stars; they indicated not only the galactic concentration, and the falling off in star numbers with increasing distance (in certain directions), but also local irregularities. And the studies of star motions revealed to Kapteyn and his successors a remarkable

complex of systematic motion which is not yet satisfactorily interpreted.

The refinement of the star counts and their extension to faint magnitudes, especially at the Mount Wilson and Groningen observatories, has carried far our knowledge of stellar distribution in the solar neighborhood. But the study of the distribution of the brighter stars of each spectral type has done more to bring to light the existence of a "local system." Formerly this local star cloud was not distinguished from the general galactic system, and its boundaries are so poorly known that we cannot now feel entirely sure of its distinctness from surrounding galactic clouds or even of its organization as a separate stellar system.

Nevertheless, the common opinion is that a local star cloud surrounds the Sun; its diameter is a few thousand light years; its population is probably numbered in millions of stars; its membership includes most of the naked-eye stars and many of the conspicuous clusterings such as the Pleiades, the Hyades, and the constellations of high temperature stars in Orion, Scorpio, and Centaurus. Less common is adherence to the provisional view of the writer that the motions of stars within the local system, and the motions of the system as a whole with respect to other star clouds of the Milky Way, give rise to the phenomenon frequently interpreted as galactic rotation. Our studies of the proper motions and radial velocities of stars deal with such a localized region near the Sun that I feel it incautious to extrapolate from a meager amount of material and form the hypothesis that the galactic system rotates as a single unit. The galactic system is perhaps a thousand times as large as the region so far explored for stellar motions.

But it may be well for the present to postpone consideration of the incompatibility between simple galactic rotation

and the existence of localized star clouds. We proceed rather to an account of a method of measuring and dissecting the section of the stellar universe which, though within a few thousand light years of the Sun, nevertheless lies beyond the range of easy trigonometric survey or measurement by means of spectroscopic parallax.

Some twenty years ago the construction of the Henry Draper Catalogue of stellar spectra was begun at the Harvard Observatory, after two decades of analyzing and classifying the spectra of the brighter stars. Professor Pickering and Miss Cannon undertook in this catalogue to list the positions and magnitudes for stars over the whole sky to approximately the ninth magnitude. The six thousand naked-eye stars were included along with about two hundred and twenty thousand telescopic objects. The catalogue, in nine volumes, was published in fifteen years. A study of the results showed that the catalogue was practically complete in the northern hemisphere for stars to the magnitude 8.25, and in the southern hemisphere to 8.75; but more than a hundred thousand stars fainter than those limits were also included. Six major groups were established in the classification of spectra, the sequence of classes bearing the letters B, A, F, G, K, M, in the order of decreasing surface temperature. Including the aberrant types and the subdivisions of the major classes, Miss Cannon has differentiated approximately fifty kinds of spectra.

The average number of stars per square degree to magnitude 8.75 for the whole sky is shown for the six major classes in Figure 1 (cf. Shapley and Cannon, Harvard Reprint 6, 1924). The conspicuously different distribution among the spectral types for fainter stars in the Milky Way is shown for localized regions in Cygnus, Figure 2, and in

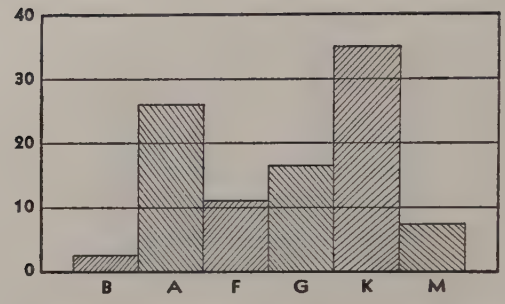

FIGURE 1. Number of stars per square degree in each spectral class, down to visual magnitude 8.75, in the Henry Draper Catalogue.

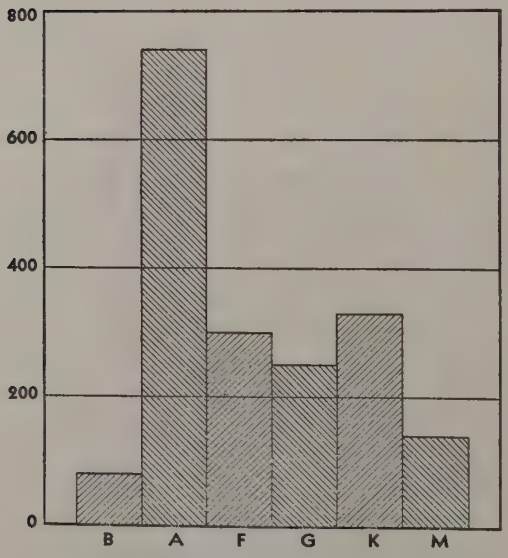

FIGURE 2. Distribution in spectral class of stars between magnitudes 10.1 and 11.0 in the Cygnus region.

Taurus, Figure 3. Further analysis of the material of the Henry Draper Catalogue shows the well known phenomenon of high concentration to the Milky Way for stars of

Classes B and A, and a more even distribution through all galactic latitudes for the cooler spectral classes.

The division into giant and dwarf stars for the classes from F to M, a highly important phenomenon early emphasized by Hertzsprung and Russell, has a bearing on the

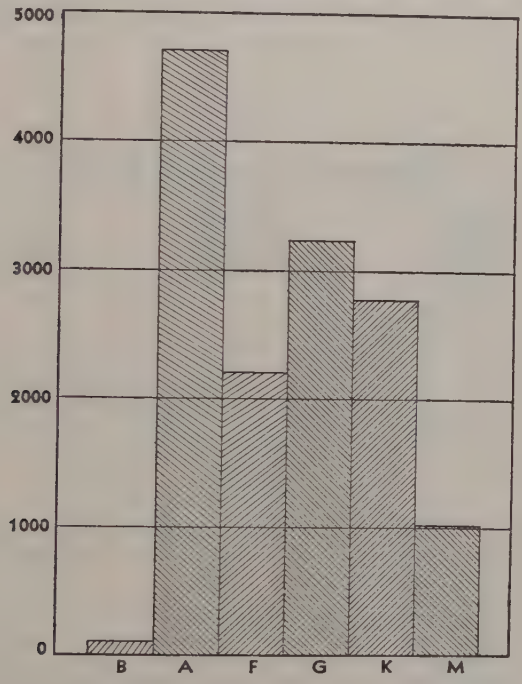

FIGURE 3. Distribution in spectral class of stars between magnitudes 10.1 and 11.0 in the Taurus region.

galactic concentration; giant K stars, for instance, are more concentrated to the Milky Way than the dwarf K stars. It is not expedient, however, to deal further here with the intricacies and peculiarities of the distribution of stars of various types. For the present purpose it need only be pointed out that whether we are considering giant stars or dwarfs, hot stars or cool, the Henry Draper Catalogue does

not get us very far into space. Eighth magnitude stars of Class A are, on the average, less than a thousand light years distant. In fact, a large majority of the stars of the statistically complete part of the catalogue are within twelve hundred light years of the Sun.

Before the catalogue was entirely published, with its valuable spectral information for the regions most com-

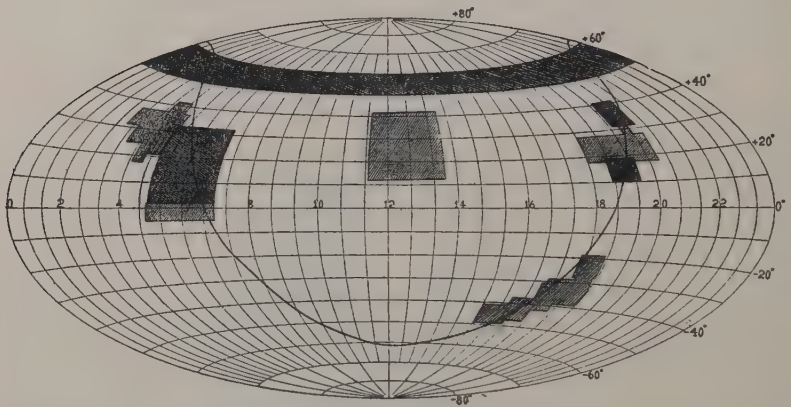

FIGURE 4. Regions covered by the Henry Draper Extension. Cross-hatch indicates classifications already published. Equatorial system of coördinates, with galactic circle superposed.

monly explored by astronomers, the studies of globular star clusters and faint variables had shown the importance of getting deeper into space, even in the analysis of the local system. An extension to the Henry Draper Catalogue was suggested, to be based on new photographs showing spectra of fainter stars and involving new determinations of apparent magnitudes. Miss Cannon and her associates immediately undertook the Henry Draper Extension, directing attention mainly to the rich and important fields in low galactic latitude (Milky Way regions). An Aitoff chart of the sky is reproduced in Figure 4 showing the progress

made up to the present time in this supplementary survey, which will extend the Henry Draper Catalogue in certain regions down to magnitude 11.5 or 12. The increase of

TABLE II

REGIONS COVERED BY THE HENRY DRAPER EXTENSION

Region	Approximate Center		Number of Stars	Approximate Area (square degrees)	Remarks
	h	°			
1. Cygnus.....	20	+37	4,000	80	Published
2. Cygnus.....	19.2	+23	13,082	220	Unpublished
3. Aquila.....	19.1	+14.8	2,800	130	Published
4. Cambridge catalogue.....	...	...	4,200	1,090	Published; Gesellschaft
5. Helsingfors-Gotha catalogue	...	...	4,200	940	Published; Gesellschaft
6. Sagittarius.....	16.8	−33	15,269	400	Unpublished
7. North Galactic Pole.....	12.6	+27	4,351	975	Unpublished
8. Taurus, Orion, Monoceros, Gemini, Auriga.	6	+18	28,100	900	Published
9. Orion.....	6	− 1.5	8,138	210	Unpublished
10. Taurus.....	4	+30	12,095	215	Unpublished
11. Large Magellanic Cloud....	5	−69.5	2,100	35	Unfinished
			98,335	5,195	

more than three magnitudes beyond the previous limit of completeness corresponds to an extension of the survey to four times the distance.

To accompany the chart of progress, Table II has been compiled. It shows that nearly one hundred thousand stars have been classified by Miss Cannon during the past eight years. The determination of the photographic magnitudes lags far behind, however, so that only half of the new spectra are published. The present state of photographic photometry is such that the determination of the magnitudes of these faint Milky Way stars is a more serious problem than the classification of their spectra; but we hope to have remedied within a few years these photometric deficiencies.

Items 4 and 5 in Table II indicate zones, extending through all right ascensions, which were especially studied at the request of Professor Schlesinger of the Yale Observatory in order to assist in his work on stellar motions. The magnitude limit for these zones is much higher than for other regions of the Henry Draper Extension, since the object in view was merely to get spectra of stars of accurately measured positions.

Until large representative areas in different parts of the Milky Way have been completed, it would be premature to analyze in detail the accumulating data on the spectra and magnitudes of faint Milky Way stars. As an illustration, however, of the manner in which the Henry Draper Extension contributes to our knowledge of the structure of the local system, I give herewith a series of diagrams illustrating the distribution of the stars of different spectral classes on the surface of the sky throughout the "Taurus" region, and also for different parts of this region curves illustrating

the frequency of Class A stars of successive intervals of brightness.

Figures 5 to 10 give plots of the positions in equatorial coordinates of stars between magnitudes ten and eleven in

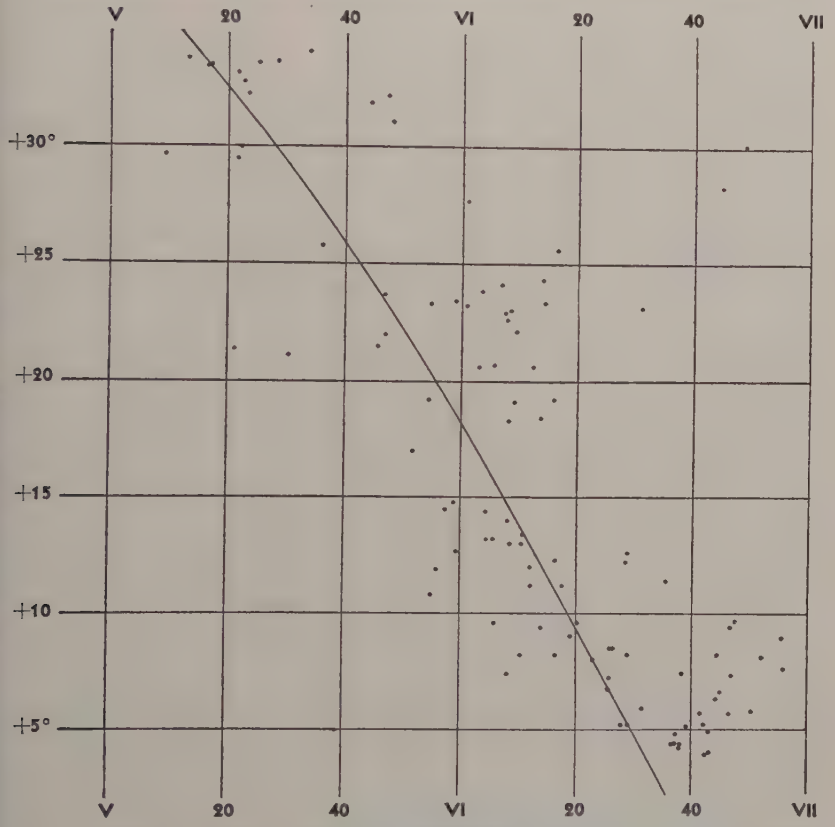

FIGURE 5. Class B stars of magnitudes 10.1 to 11.0 in the Taurus region of the Henry Draper Extension. Coördinates are right ascension and declination. The heavy curved line represents the galactic circle.

the Taurus region, which extends over about nine hundred square degrees and includes sections of several of the neighboring constellations. The course of the galactic circle through the region is indicated.

The relative infrequency of Class B stars, already shown in Figure 3, is well illustrated in Figure 5. For a first approximation we can consider the Class B stars in this in-

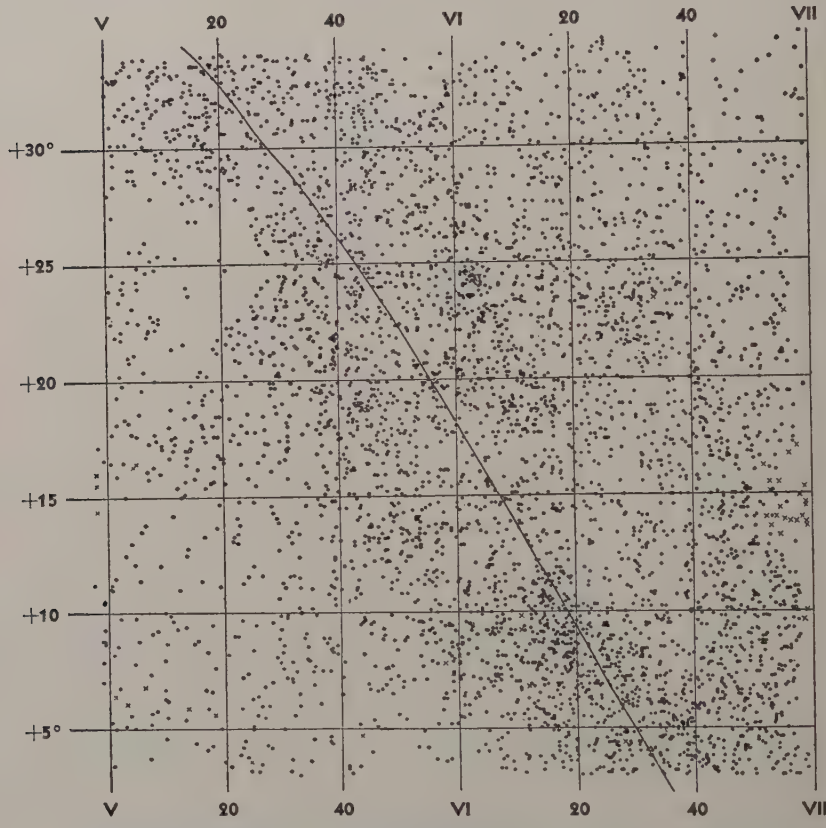

FIGURE 6. Class A stars of magnitudes 10.1 to 11.0 in the Taurus region of the Henry Draper Extension. In this and the four following diagrams the crosses indicate stars taken from the Henry Draper Catalogue.

terval of apparent magnitude as approximately five thousand light years from the Sun; brighter Class B stars are of course generally nearer, and those fainter than the eleventh magnitude more remote. Similarly for the other

classes the respective plots present the distribution throughout a definite, relatively small, interval of distance from the observer. What this distance is varies from class to

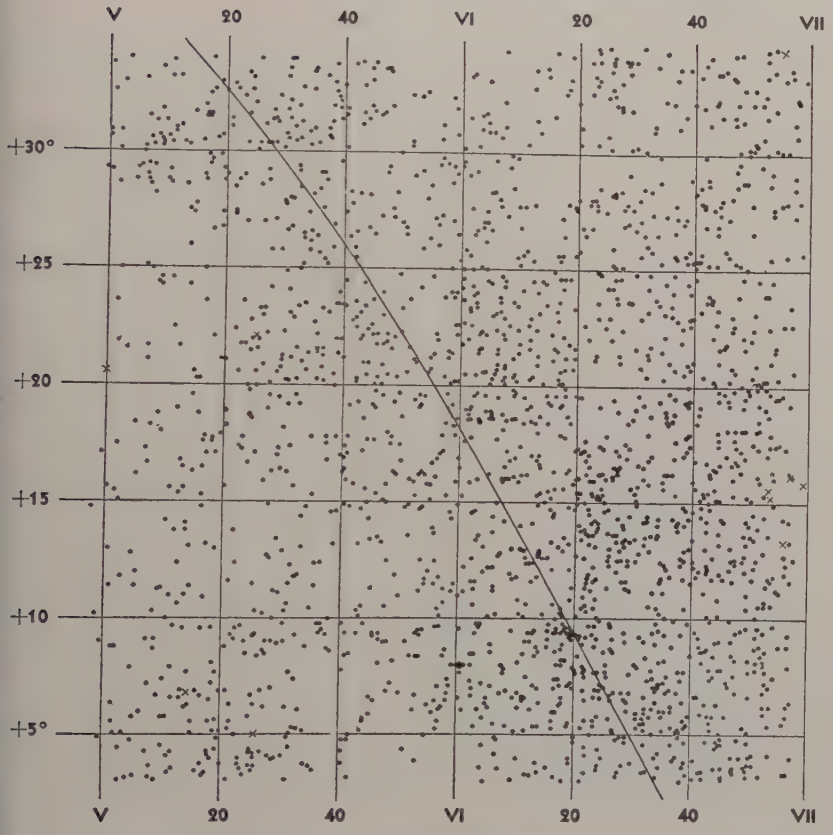

FIGURE 7. Class F stars of magnitudes 10.1 to 11.0 in the Taurus region of the Henry Draper Extension.

class, depending of course on the absolute luminosities of the different types of stars. For Classes G, K, and M, in which giants and dwarfs are mixed, two intervals of distance are represented.

A general consideration of the distribution figures shows least concentration to the galactic circle for solar type stars (Class G); they are probably largely dwarfs. A higher concentration is shown by stars of Class A, and also a dis-

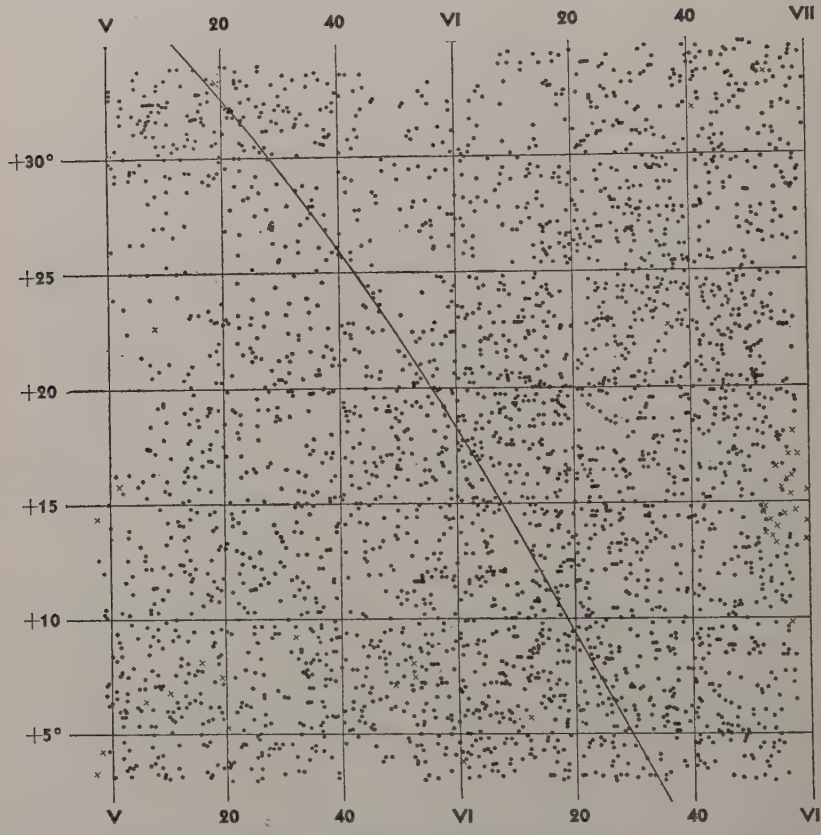

FIGURE 8. Class G stars of magnitudes 10.1 to 11.0 in the Taurus region of the Henry Draper Extension.

tinct unevenness in their frequency throughout the field. The most important deficiency for the Class A stars is at right ascension $5^h\ 20^m$, declination $+25°$. The same "hole in the sky" is shown clearly for some of the other classes;

it undoubtedly indicates the presence of an obscuring dark cosmic cloud, and it is in the discovery and location in space of such obscurations that the Henry Draper Extension may be most useful.

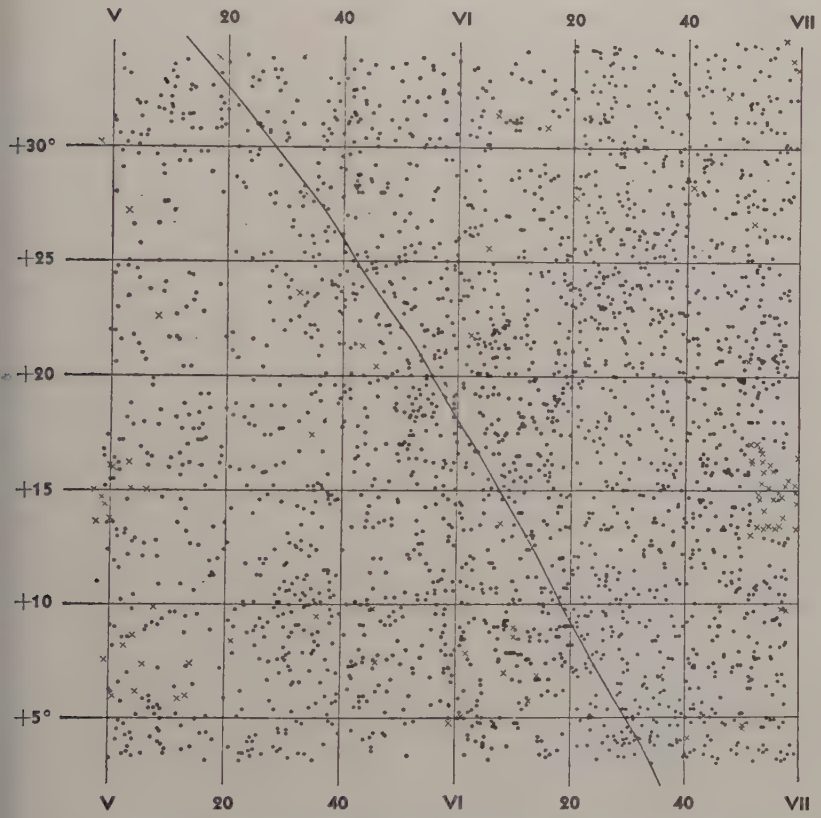

FIGURE 9. Class K stars of magnitudes 10.1 to 11.0 in the Taurus region of the Henry Draper Extension.

To look further into the form and effect of the obscuration at $5^h\ 20^m$, $+25°$, and also in the field fifteen degrees further south, I have presented in Figures 11 and 12 a series of distribution plots of Class A stars. All the Class A

stars from the sixth to the eighth magnitudes are shown in Figure 11a, the data being taken from the Henry Draper Catalogue. For magnitudes eight to nine the star positions are plotted in Figure 11b; for nine to ten in Figure 12a;

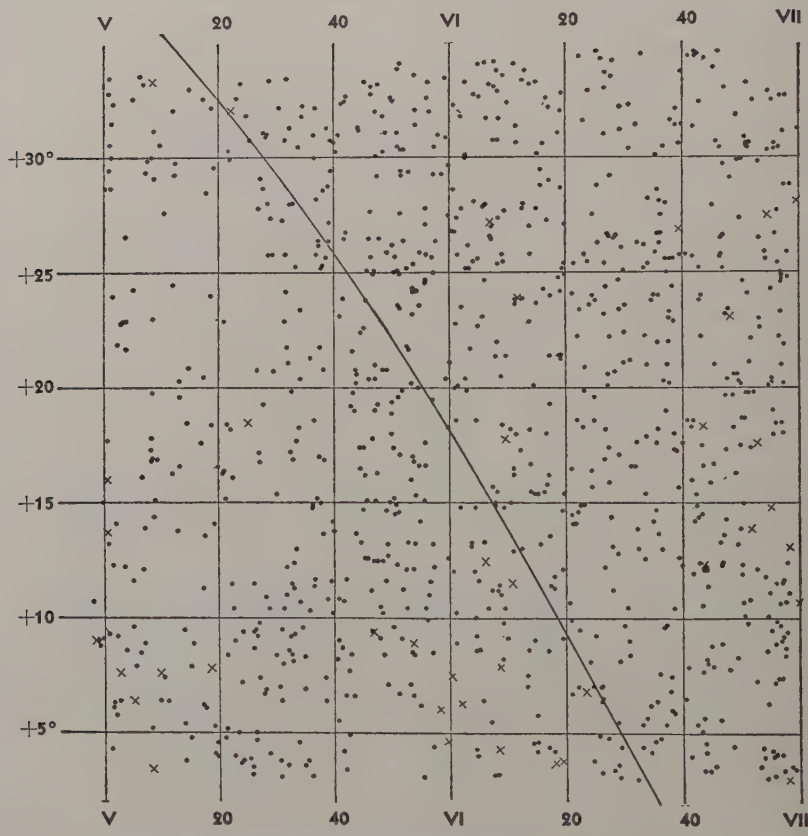

FIGURE 10. Class M stars of magnitudes 10.1 to 11.0 in the Taurus region of the Henry Draper Extension.

for ten to eleven in Figure 6; and for stars fainter than the eleventh magnitude, as far as data are available, in Figure 12b. This last plot shows a number of stars appearing in the region that is nearly void of brighter stars. I believe

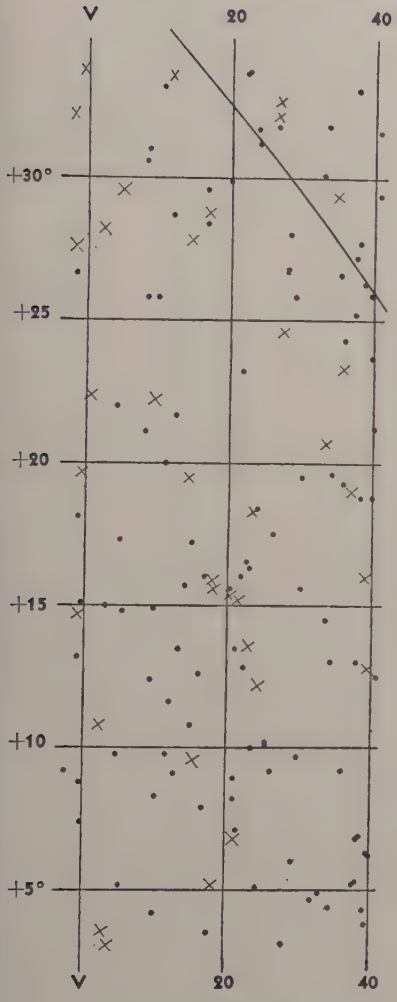

FIGURE 11a. Class A stars in the first forty minutes of the Taurus region. Crosses indicate stars of magnitudes 6.1 to 7.0; dots, those of magnitudes 7.1 to 8.0. These stars are in the Henry Draper Catalogue.

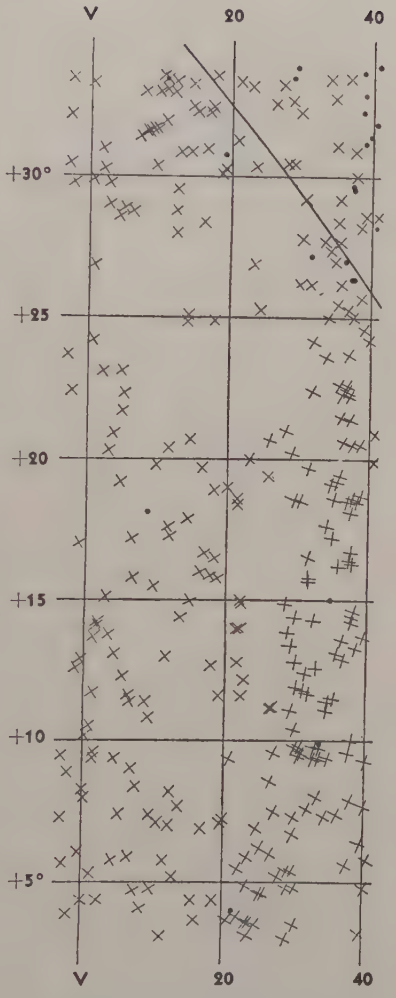

FIGURE 11b. Class A stars, in the Taurus region, of magnitudes 8.1 to 9.0. Crosses indicate stars in the Henry Draper Catalogue; dots, stars in the Henry Draper Extension.

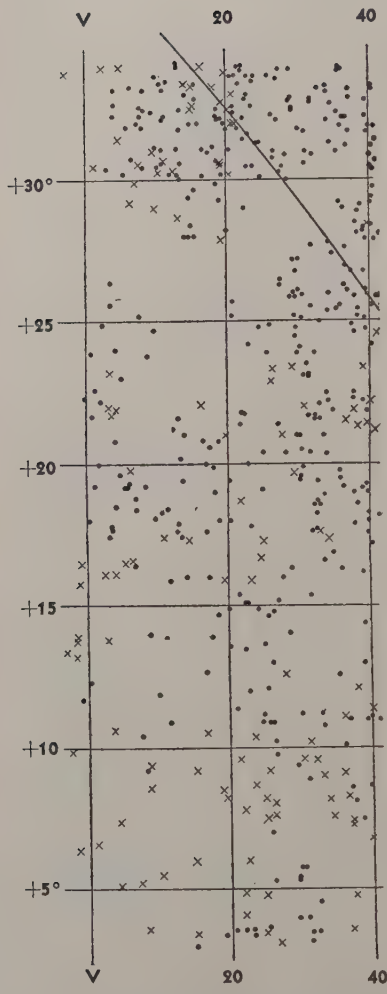

FIGURE 12a. Class A stars, in the Taurus region, of magnitudes 9.1 to 10.0. Crosses indicate stars in the Henry Draper Catalogue; dots indicate stars in the Henry Draper Extension.

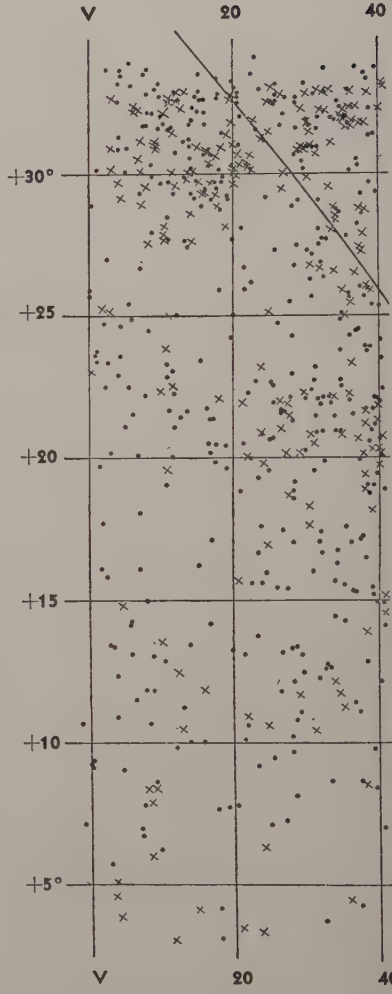

FIGURE 12b. Class A stars, in the Taurus region, of magnitudes 11.1 and fainter, in the Henry Draper Extension. Crosses indicate stars from 11.1 to 11.5; dots indicate stars fainter than 11.5.

this indicates that the obscuring cloud is not completely opaque, but merely cuts down the light of the more distant stars by two or three magnitudes.

The obscuring nebulosity of the Taurus region extends northward and westward for many degrees, beyond the

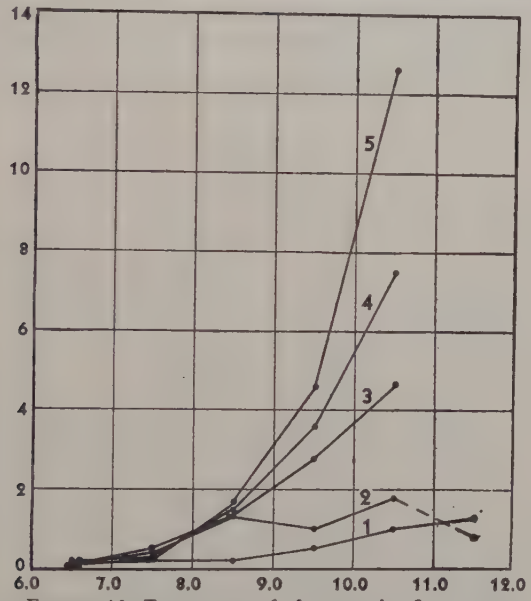

FIGURE 13. Frequency of A stars in five areas in the Taurus region. Ordinates are numbers per square degree. Abscissae are photographic magnitudes.

limits of the plots here given. In order to investigate further its extent and its distance from the Sun, the Henry Draper Extension is being spread over the whole region affected. When the material is available we shall be able to consider thoroughly the position of the Taurus nebulosity; and perhaps by making special spectroscopic studies of the various classes of stars in or beyond the nebulosity we may be able to learn more concerning the nature of the materials of which such cosmic clouds are composed.

It is clear from Figures 11 and 12, with the addition of Figure 6, that the number of Class A stars increases with decreasing brightness at different rates in different parts of the sky. In heavily nebulous regions the increase is slow; in transparent regions where the remote A stars are not lost by intervening nebulosity the increase is rapid. I have selected five different areas in the Taurus region for which the frequency curves are tabulated in Table III and plotted

TABLE III

NUMBER OF CLASS A STARS PER SQUARE DEGREE IN TAURUS

Area	Number of Square Degrees	Photographic Magnitude					
		6–7	7–8	8–9	9–10	10–11	11–12
1	35	0.1	0.2	0.2	0.5	1.0	1.3
2	99	0.1	0.4	1.3	1.0	1.8	0.8
3	50	0.1	0.5	1.3	2.8	4.7	...
4	75	0.2	0.3	1.5	3.6	7.5	...
5	62	0.2	0.3	1.7	4.6	12.6	...

in Figure 13. The areas are arranged in order of increasing richness in stars between magnitudes ten and eleven; Area 1 is the most heavily obscured, Area 5 is nearly if not quite free of obscuration. Although there is little difference in the number of Class A stars per square degree brighter than the eighth magnitude, at the tenth magnitude Area 5 is thirteen times as rich as Area 1. Obviously the form of the frequency curve of apparent magnitude depends on the area observed.

The average giant star, with a luminosity a hundred times that of the Sun, is about five thousand light years distant

when of apparent magnitude 11.5, which is the working limit of the Henry Draper Extension. This means that the completion of the Extension all around the Milky Way will give us most of the giant stars throughout the local system and, out to distances of two or three thousand light years, some hundreds of thousands of less brilliant bodies. Although distances of the individual stars will not be obtained, the material should be of considerable value in statistical investigations of the structure of the local star cloud.

Useful though it may be for the analysis of the local system, the Henry Draper Extension will deal very little with most of the star clouds that make up the Milky Way. Except for their supergiant stars, the clouds are composed of objects fainter than magnitude 11.5. We may be able to get some rather uncertain information concerning their structure from undifferentiated star counts; some rather better knowledge from surface photometry of the Milky Way. But a more direct way of investigating the distances and structure of the Milky Way star clouds is described in the next section. Leaving the local system, we enter the fourth territory of our sidereal explorations and tackle the difficult problem of measuring directly the dimensions of the galactic system.

IV

THE MILKY WAY

SINCE the star that varies in light plays a considerable part in the measurement of distances to the star clouds of the Milky Way and to external galaxies I shall describe in this section some of the current investigations of variable stars at the Harvard Observatory.

First it should be noted that the distance of a star is simply related to its apparent magnitude, as measured with reference to adopted standards, and to its absolute magnitude or intrinsic luminosity. When the intrinsic luminosity of a star can be determined from some characteristic of its light or behavior, it is a simple matter to measure the star's apparent magnitude and compute the distance. This method is used, as mentioned in Section II above, in the spectroscopic determinations of stellar distances, where the relative intensity of lines in the spectra gives the clue to absolute magnitude. The same procedure is used with variable stars, the intrinsic luminosity being judged on the basis of various observable properties.

For eclipsing variables the dimensions of the components, their relative brightnesses, and their spectral types help to fix the absolute magnitudes; for Cepheid variables the length of the period is the clue to the star's output of radiation, and a serviceable period-luminosity relation has been discovered. Fortunately, the various kinds of variable stars are giants or supergiants—they may be seen at great distances, and therefore become useful for measuring the remotest galaxies that our telescopes can resolve.

There are several important astronomical problems connected with the study of eclipsing binaries. We might mention, for instance, that the analyses of their light variations provide our chief source of direct information on the densities of stars; they tell of the stellar forms in tidally disturbed binary systems; they occasionally give the linear dimensions of stellar bodies, and they furnish much information on the sizes, shapes, and inclinations of the orbits of close double stars. From the light curve of an eclipsing binary we also deduce an estimate of the distance; and it is for this reason that eclipsing binaries become important in galactic explorations, since we frequently find such variables among the faintest objects on the photographic plates.

Orbits of more than a hundred eclipsing binaries have been computed from their light curves. Frequently the solutions are inherently indeterminate; at other times they are indefinite because of the low quality of the photometric observations on which the graphs of the periodic variations are based. In the past most of the light curves of eclipsing stars have been derived from visual observations. Relatively few good light curves have been based on photographic observations.

To improve existing light curves and to add new material for the further photographic study of eclipsing binaries a special research program was recently inaugurated at the Harvard Observatory with the assistance of a grant from the Permanent Science Fund of the American Academy of Arts and Sciences. Several thousand estimates of magnitudes have been made for ten or twelve stars and the computation of their orbits is under way. The light curves obtained from the photographic observations are of relatively high quality; the periods of variation have been accurately determined, sometimes to a millionth of a day. For

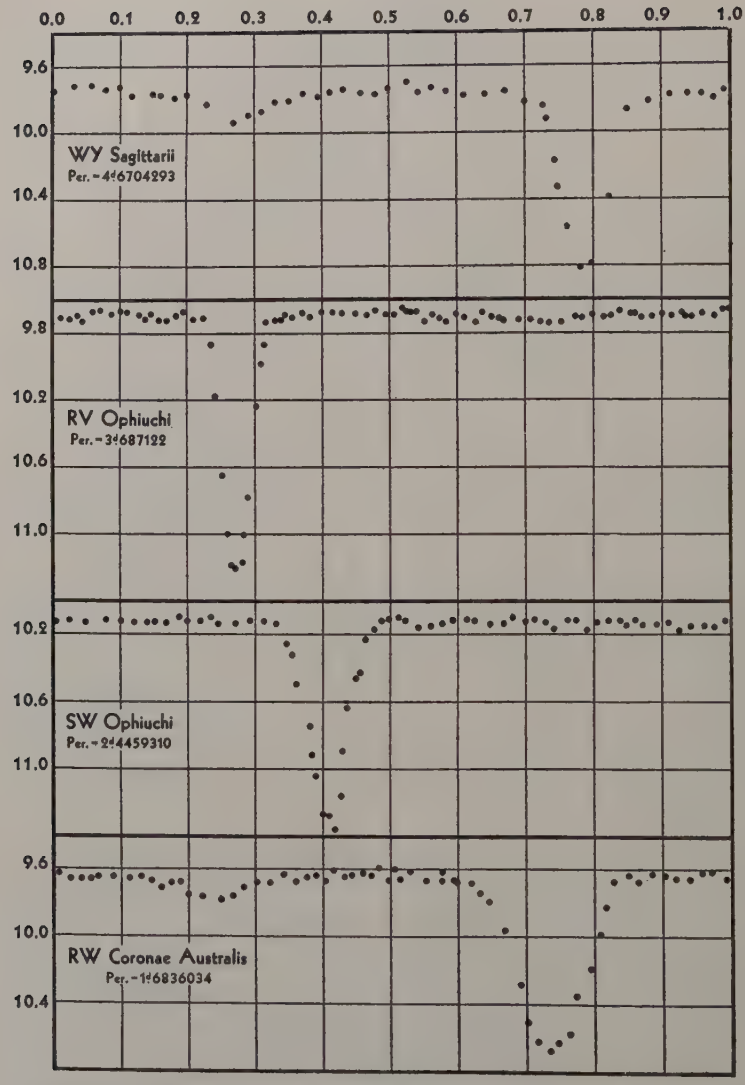

FIGURE 14. Light curves of eclipsing binaries. Ordinates are photographic magnitudes; abscissae are fractions of the periods.

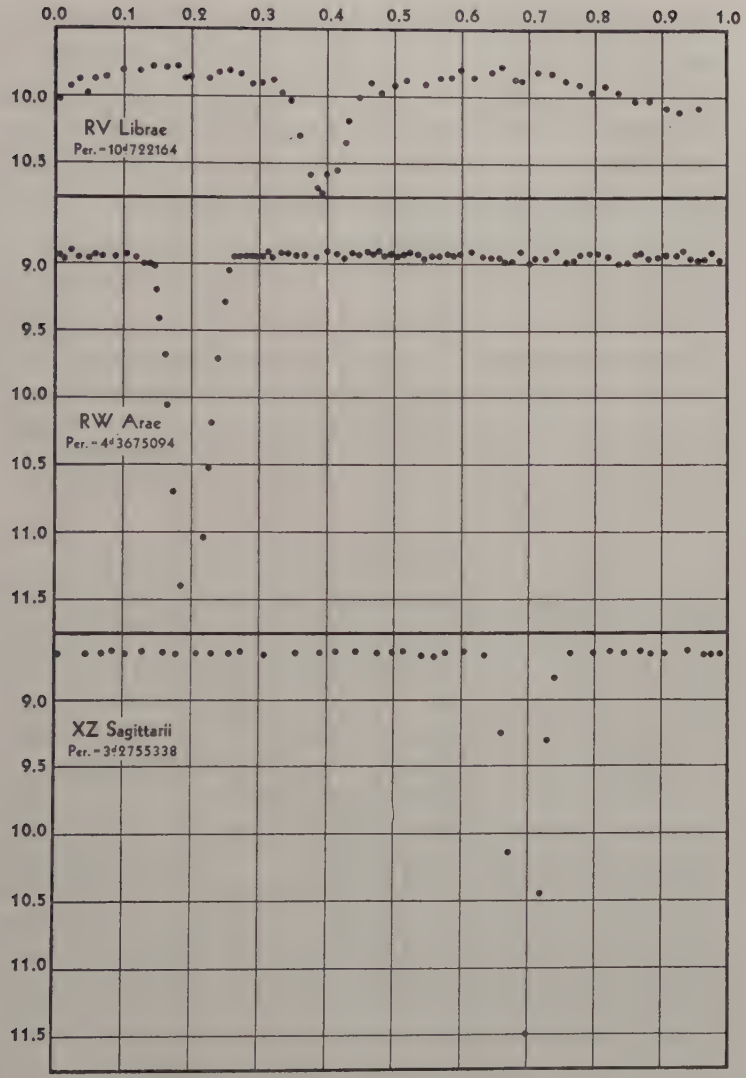

FIGURE 15. Light curves of eclipsing binaries. Ordinates are photographic magnitudes; abscissae are fractions of the periods.

some of the stars the observations show shallow secondary minima and the slightly rounded maxima that indicate the gravitational deformation of the component stars of the binary. In Figures 14 and 15 several of the new photographic light curves are shown. Each plotted point represents, in general, the mean of ten observations.

The analysis of these light curves will show that some of the binaries are composed of nearly equal stars, while the components of others are very unequal in size, most of the light coming from the smaller members. Some of the eclipses are only partial, while for others the small companion is completely occulted by the larger at primary eclipse and is projected fully on its disk at the shallow secondary eclipse.

The Cepheid variable star, which now has the distinction of being the astronomer's most important tool in measuring the universe, is found sparingly among the naked-eye stars, infrequently also throughout the local system, but in considerable abundance in and around the Milky Way star clouds, in the globular star clusters, in the Magellanic Clouds, and in the nearer of the spiral galaxies. The periods vary in length from a few hours to a month or more, and the longer the period the higher the luminosity and the redder the spectral class. When the periods are some weeks in length the stars are supergiants and, even when at a distance of a hundred thousand light years, can be recorded with moderate-sized telescopes.

The period-luminosity relation for Cepheid variables gives a simple way of estimating the distances not only of individual Cepheids but of the clusters and star clouds in which they are situated. Many observations must be accumulated, however, to permit the derivation of light curves

and periods. Frequently fifty or a hundred photographs of a Cepheid variable are necessary before the period can be determined, the apparent magnitude satisfactorily measured, and the distance deduced. Hence the work of exploring the Milky Way with the aid of Cepheid variables is a laborious process; but students of the subject are agreed that no method at present known is more satisfactory for estimating great distances.

Among the current or very recent investigations on Cepheid variables at the Harvard Observatory are:

(1) A new determination of the period-luminosity relation;
(2) Coöperative studies with a score of other observatories on some fifty selected variable stars of the Cepheid class—studies which involve for Harvard observers work on the periods, the photographic light curves, the magnitudes of comparison stars, the variations in spectral class throughout the period of each variable, and the collection of approximately two hundred special photographs on each star;
(3) The discovery and cataloguing of eight hundred new Cepheid variables in the Large Magellanic Cloud;
(4) The systematic investigation of the light curves of more than a hundred variables, and the dependence of the form of light curve on period length;
(5) Detailed spectral analyses of the brightest Cepheids;
(6) The change with brightness for many Cepheid variables of the degree of ionization of the calcium in the stellar atmosphere.

Many of these studies of Cepheids are only indirectly related to exploration in the Galaxy. They involve problems of stellar temperature, stellar evolution, and the cause

of Cepheid variability. Others bear directly on the problems of the absolute magnitudes of Cepheids and their distribution in space, and thus lead directly to knowledge of galactic dimensions.

Long period variable stars showing variations considerably larger, in general, than Cepheid variables, and with periods ranging in length from one hundred to five hundred days or more will probably also be of importance in measuring the distance to galactic star clouds. As yet we do not know a great deal concerning their intrinsic luminosities or the dependence of intrinsic luminosity on length of period, spectral class, or shape of light curve.

Certain data on the motions of these stars, examined by various investigators, indicate that at maximum light the variables have between one hundred and five hundred times the luminosity of the Sun. The frequency curve of the maximum magnitudes of long period variable stars in a remote Milky Way field is compared in Figure 16 with the frequency curve of magnitudes of Cepheid variables with periods less than one day. If it is assumed that the stars of the two types are at the same distance, the frequency curves indicate that the long period variables are intrinsically a magnitude brighter photographically than the Cepheids. A further indication of the high luminosity of the long period variable stars is obtained from the Large Cloud of Magellan, in which two long period variables, if they are not superposed stars, have at maximum the luminosity of Cepheid variables with periods of approximately fifty days. A similar indication may be derived from a study of long period variables in the globular cluster 47 Tucanae.

Taken altogether, it appears that the absolute magnitude of long period variables at maximum is high, and will in

time be extensively and successfully used in the estimation of great distances. Meanwhile a vast amount of observational work is carried on, photographically at the Harvard Observatory and visually by several variable star societies, in collecting data on the brighter and nearer long period variables and preparing these stars for the increasingly important rôle they will some day fill.

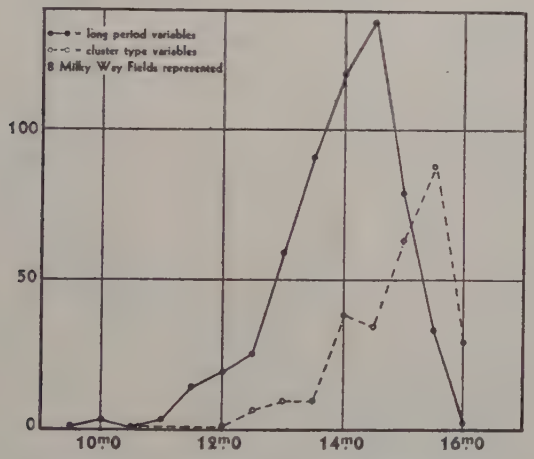

FIGURE 16. Frequency of long period and of Cepheid variables in the Milky Way. Coördinates are numbers of stars and photographic magnitudes.

A fourth kind of distance-indicating variable star is the nova. Many of these intrinsically very luminous objects appear on the Harvard plates and their distribution in the sky has contributed to our knowledge of galactic dimensions and has indicated, for instance, the probable existence of a massive nucleus of the Milky Way system in the direction of the constellation Sagittarius. At maximum brightness the average nova, according to Lundmark's extensive investigations, has more than ten thousand times the Sun's luminosity. Novae became important, therefore, in the determination

of distances of external galaxies, and Hubble has used them most effectively, along with the giant Cepheid variable stars, in studying spiral nebulae that lie at a distance of a million light years.

From the foregoing paragraphs we see how four types of variable stars—eclipsing binaries, Cepheid variables, long period variables, and novae—are useful in measuring space. Such variables can be studied satisfactorily even when so distant and faint that spectroscopic methods are quite impossible and trigonometric and proper motion measures are hopelessly inadequate. They provide an easy entry to the Milky Way star fields in which they are embedded.

About seven years ago a program for the systematic photography of Milky Way variable stars was inaugurated to supplement the plates of the Harvard sky patrol. The patrol supplies ample material for variables brighter than the twelfth magnitude but contributes too little on variable stars associated with the Milky Way star clouds. In this new variable star program the whole of the galactic belt is covered systematically by the photographic telescopes assigned to the problem. In three lines along the galactic circle a total of 196 centers were chosen in such a manner that adjacent fields overlap. The arrangement of the fields is shown in Figure 17, which is a map of the sky, showing the equatorial coördinate system with the galactic circle and the ecliptic traced in. For comparative purposes 72 variable star fields in various high galactic latitudes, as shown on the map, have also been selected for study.

Several thousand photographs have been taken on the program with the telescopes at Bloemfontein and at Cambridge. Particular emphasis has been given to the southern Milky Way, not only because of the greater richness in

FIGURE 17. Distribution of Milky Way Fields for the variable star program.

variable stars and in other objects of interest, but because the northern sky is being more completely studied at other observatories than the regions in the south. On only a few of the 268 variable star fields have a sufficient number of photographs been collected as yet to permit a thorough study of the variable stars. The regions under closest investigation at the present time are in the southern Milky Way from Centaurus to Aquila. It is in this quadrant that the "galactic nucleus" lies, and here we find the greatest frequency of stars for the whole galactic system.

The photographs of the southern Milky Way are made principally with the 10-inch Metcalf triplet, with which an 8 by 10-inch plate covers approximately one hundred square degrees. Stars fainter than the sixteenth magnitude are shown, and in general the number of variable stars found increases steadily with decreasing brightness. Some fields, however, are much richer than others; and in a very preliminary way we have evidence that certain types of variables favor different regions of the Milky Way. In high galactic latitudes, for instance, Miss Hughes has found an unexpectedly large number of faint eclipsing binaries and faint Cepheids of the cluster type (periods less than a day), but none of the high luminosity Cepheids of longer periods.

A recent tabulation of numbers of new variable stars discovered in the course of the Milky Way survey is given in Table IV.

The Milky Way variable star survey is currently producing much interesting material concerning individual variable stars and the relative numbers of the different types; but the long range goal of the Harvard survey is a determination of the distances and arrangement of the various sections of the Milky Way system. The Leiden, Berlin-Babelsberg, and Sonneberg observatories are also contributing

actively to the study of variable stars and the related problems.

One of our first contributions from the faint variable stars to knowledge of galactic structure is the provisional

TABLE IV

VARIABLES DISCOVERED IN THE MILKY WAY

(in percentages)

Milky Way Field	Long Period	Cluster Type	Short Period	Eclipsing	Irregular and Unknown	Total Numbers
167	30	22	19	21	8	151
169	46	20	10	15	9	135
173	35	26	11	13	15	54
175	35	24	13	16	12	270
184	45	15	27	4	8	350
185	41	29	16	2	12	385
187	45	14	20	2	19	700

VARIABLES IN FIELDS OUTSIDE THE MILKY WAY

(in percentages)

Milky Way Field	Long Period	Cluster Type	Short Period	Eclipsing	Irregular and Unknown	Total Numbers
213	14	42	8	36	0	36
215	5	35	20	40	0	20
217	0	80	20	0	0	10

determination of the distance of the star cloud on which Milky Way Field 185 is centered. Miss Swope and the writer have concluded that the cluster type Cepheids found in great numbers for that particular field are connected with the star cloud and are, in the mean, nearly fifty thousand light years distant. The variable stars in the neighboring

field 187 are of similar magnitude and distance, and we are led to the tentative suggestion that the dense star clouds in the Sagittarius-Scorpio-Ophiuchus region of the Milky Way form something of a nucleus of the whole galactic system. These star clouds are badly marked up with intervening dark nebulosities, and it is possible that the magnitudes of the variables and the distances are disturbed by partially obscuring dust clouds. Further study of the variable stars throughout the region will throw light on the effects of the obscuration; but meanwhile we note that it is the globular star clusters rather than the Milky Way star clouds which indicate that the center of the galactic system lies in the Sagittarius region of the Milky Way.

V

THE SYSTEM OF GLOBULAR CLUSTERS

THE diameter of the Milky Way is certainly not less than a hundred thousand light years. It may be, and probably is, much larger. Undoubtedly the globular star clusters, which are observed along the borders of the Milky Way and sparingly in high galactic latitudes, form a system that extends throughout a region more than two hundred and fifty thousand light years in diameter.

The galactic system may be coextensive with the globular clusters; or it may be that the clusters, the star clouds of the Milky Way, and the local system surrounding the Sun form a complex system of higher order than a simple galaxy. We shall in time know about these matters; for the present we shall consider that the supersystem of a hundred globular clusters constitutes the fifth stage in our explorations and marks the point where we pass from considering various parts of the galactic system to the treatment of external galaxies.

The problems of star clusters have been presented fully in a recent Harvard publication[1] and further concentrated study of the clusters awaits the 60-inch reflecting telescope at the Bloemfontein station of the Observatory. Two current investigations, however, should be mentioned.

1. Most of the Cepheid variables in globular clusters have been found to have periods of less than a day and contribute little to our knowledge of the course of the

[1] Harv. Mon. No. 2, 1930.

period-luminosity curves. But there are a few classical Cepheids (with periods greater than a day), and Mrs. Hogg has completed as thorough a study of them as is possible with existing photographs. In addition to tests of the period-luminosity relation in globular clusters, she has determined the periods and average median magnitudes of many cluster type Cepheids in two bright globular clusters hitherto unstudied—Messier 4 and N. G. C. 362.

2. Most globular clusters look alike at the first glance, being radially symmetrical swarms of stars highly concentrated. But on close analysis differences and irregularities are found, and Mr. Miller has been making contour maps of the luminosity distribution in some of the bright northern globular clusters, basing his work chiefly on star counts for photographs of different exposure lengths.

Much remains to be done on the system of globular clusters, though we probably know this territory better than any of the other seven that concern us in our galactic explorations. We should like to examine further the individual stars in the clusters, photometrically and spectroscopically —for light variations and for motions. In particular we must work to find the link, if any, between the typical globular cluster and the open galactic clusters, or between the globular systems and the smaller spheroidal nebulae that are placed, with the spiral nebulae, in the category of external galaxies.

The relationship of globular clusters to other stellar organizations may be most easily elucidated by the study of those in the Magellanic Clouds, which are the nearest of the outside galaxies and the objects towards which our explorations now lead.

VI

THE CLOUDS OF MAGELLAN

THE two large isolated nebulous patches of light in the southern sky, which have attracted the attention of southern travellers from the time of Magellan onward, are a source of much useful information in the measurement and understanding of all stellar systems. Studied from the southern stations of the Harvard and Lick observatories, in Peru and Chile, they have proved a happy hunting ground in which to find gaseous nebulae, stars of the peculiar P Cygni type, Class O supergiant stars, star clusters of various sorts, and, perhaps most important of all, a wealth of variable stars of the Cepheid type. The Small Cloud is the system for which Hertzsprung first estimated a distance by means of Cepheid variables, following Miss Leavitt's pioneer work on the relation between the brightness and periods of the variable stars. In more recent studies at the Harvard Observatory we have established the period-luminosity relation in the Small Cloud in the form that is currently used for the estimation of the distances of Cepheid variables.

In both past and current investigations of the Clouds of Magellan we have taken full advantage of our position as external observers; future studies will still further exploit the advantages of this objectivity. The Clouds are the nearest of isolated external galaxies and the forthcoming analyses of the spectra, light variations, distribution, and motions of their stars, clusters, and nebulae will reflect on

the problems of our local system and of the star clouds in the Milky Way. The investigations of the Magellanic Clouds that are now in progress at the Harvard Observatory will be briefly described in the following pages, the progress report being prefaced by a brief description of the Clouds in order to orient the reader with regard to these nearest representatives of the spiral nebula family.

The Large and Small Magellanic Clouds are in the southern constellations of Dorado and Tucana, respectively, with angular diameters of approximately 7 and 3.5 degrees. Both are found to be at a distance of about ninety thousand light years, if we use for deriving this value the reference system now generally though provisionally adopted.[1]

The speed of recession is +275 kilometers per second for the Large Cloud and +170 kilometers per second for the Small, and Hertzsprung has shown reason for believing that the two Clouds move along parallel paths. I think it likely that the major part of the observed recessional speeds is but a reflection of the motion of the local system with respect to the main mass of the Galaxy, including the globular star clusters and the Clouds of Magellan. Luyten has made a provisional study of the proper motions of stars in the field of the Large Magellanic Cloud.

On early photographs with the Bruce telescope Miss Leavitt discovered nearly eighteen hundred variable stars in the two Clouds, and up to the present the periods and light curves of two hundred have been determined. The positions and descriptions of many of the gaseous nebulae have

[1] All the distances mentioned in the last five sections of this article are based on the zero point of the period-luminosity relation which is given in Harvard Observatory Monograph No. 2. In the course of a few years a definitive revision will be possible, and then the distances here given can all be changed by a constant factor.

been published by Harvard investigators and preliminary measures made of the included globular star clusters.

The foregoing citation of observational results covers most of the knowledge of the Clouds up to the beginning of the current year. The following paragraphs report on investigations now in progress.

a. The Supergiant Stars. A survey some years ago of the Small Magellanic Cloud showed that it contains more than one hundred thousand stars brighter than absolute magnitude zero, with its most luminous members of magnitude −6. A recent survey of the distribution of magnitudes of stars in the Large Magellanic Cloud has led to the following estimates of its total population of highly luminous stars:

ABSOLUTE PHOTOGRAPHIC MAGNITUDE	TOTAL NUMBER OF STARS
]−5.0	735
−5.0 to −4.5	943
−4.5 to −4.0	1,460
−4.0 to −3.5	2,401
−3.5 to −3.0	3,262
−3.0 to −2.5	6,832
−2.5 to −2.0	11,077
−2.0 to −1.5	16,082
−1.5 to −1.0	23,172
−1.0 to −0.5	45,073
−0.5 to 0.0	103,354
	214,391

Since the Large Cloud covers forty square degrees, we must expect the adventitious appearance on the photographs of a large number of stars of our own system. The numbers just given have been corrected for these superposed

stars, using statistical tables derived by van Rhijn. Stars brighter than photographic absolute magnitude −2 are commonly referred to as supergiants, and the Cloud contains more than twenty thousand such objects. Stars brighter than absolute magnitude −5.0, which corresponds at the distance of the Large Cloud to apparent magnitude 12.1, are more than fifteen thousand times as bright as the Sun. Without further study of the spectra and motions we cannot distinguish these individual stars of enormous luminosity from the individual low luminosity superposed stars of our own system; all that we can say without such analysis is that in both of the Clouds there must be several hundred stars of this abnormally high real brightness; at the same time we should remember that similar stars are known in our local system where we can pick out a few individual supergiants, but cannot yet make a census.

b. Spectra of the Supergiants. The Henry Draper Catalogue of stellar spectra includes practically all stars brighter than magnitude 8.5 in the region of the Clouds of Magellan, and Miss Cannon has gone to much fainter magnitudes for objects of special spectral classes. As a part of the Henry Draper Extension, described in an earlier section, the classification of the stars in and around the Large Cloud, approximately to photographic magnitude 12.0, is now under way. When complete, this classification, even though provisional for a number of the fainter stars, will be of high importance for the study of stars of highest luminosity. Partial results are now available. The following tabulation refers almost wholly to stars between magnitudes 10 and 12. It gives in the second column the number of stars for each spectral class in or in front of the Large Cloud; the last column gives the corresponding numbers for a smaller control field adjacent to the Cloud. The distribution is

CLASS	CLOUD	FIELD
O	8	0
B	28	0
A	66	10
F	153	35
G	771	206
K	768	172
M	385	77
	2179	500

illustrated in Figures 18 and 19, where it is seen that the Class O and Class B stars are entirely absent from the field.

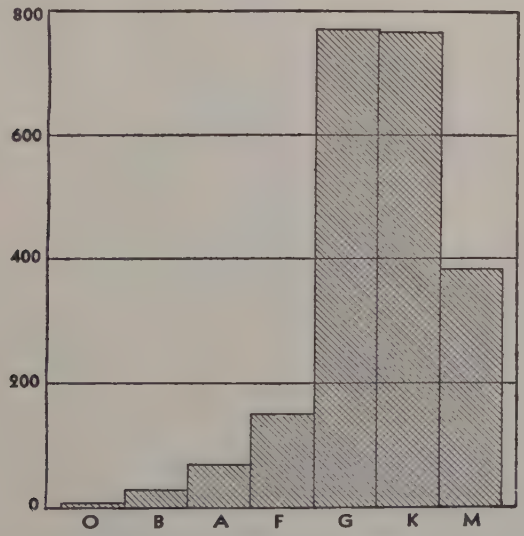

FIGURE 18. Distribution of spectra for the Large Magellanic Cloud.

But the diagrams in other respects are so nearly alike that we can fairly maintain that Figure 18 also refers almost wholly to non-Cloud stars. Perhaps, in addition to the stars of

Classes O and B, some of the Class K and Class M stars are members of the Cloud, but otherwise relatively few of the members are brighter than the twelfth magnitude unless their distribution among the spectral types is similar to that of dwarfs.

c. Open Clusters. The brightness of the individual stars

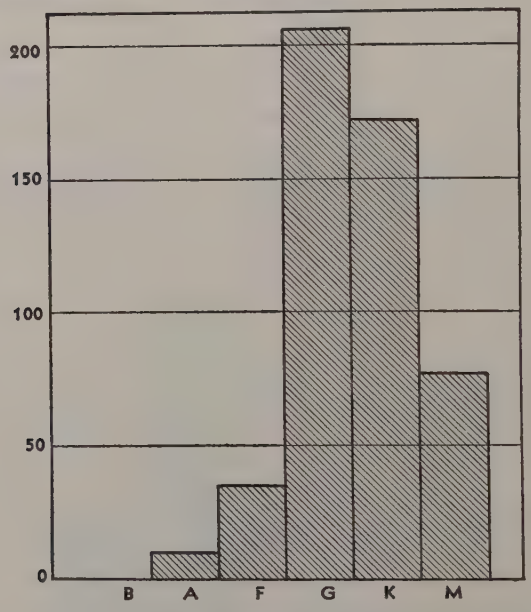

FIGURE 19. Distribution of five hundred spectra in a region on the southern border of the Large Magellanic Cloud.

in the different open clusters in the Large Cloud may have a direct bearing on our study of the open clusters in the galactic system. To estimate the distance of the galactic clusters we have in the first approximation assumed that the brightest stars are of about the same intrinsic luminosity in all clusters. Similar assumptions have been made by others who have worked on problems of galactic clusters. A current examination of the brightness of the clusters in the

Large Cloud shows, however, that the assumption is precarious. In Figure 20 the frequency of the brightest apparent magnitude for 153 open clusters is plotted. The magnitudes, estimated to the nearest half magnitude, are referred to the International Standards and apply in each cluster to the fifth brightest star. In order to avoid errors due to superposed objects, it is safer to take the fifth star in

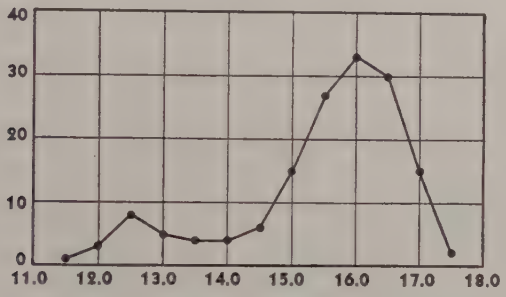

FIGURE 20. Frequency curve of the magnitude of the fifth star in open clusters of the Large Magellanic Cloud. Coördinates are numbers of clusters and photographic magnitudes.

each cluster rather than the first as an indicator of the maximum luminosity.

The frequency curve indicates in the first place the exceedingly high luminosity of the brightest stars in some of the open clusters, and in the second place the wide dispersion in luminosity. It may be that further information on the spectral classes will enable us to set up spectral criteria that will to some extent correlate with absolute luminosity; but for the present the curve serves chiefly to discredit earlier assumptions of the comparability of the brighter stars from one open cluster to the next.

d. Discovery and Distribution of Variable Stars. Probably the most interesting feature of the Magellanic Clouds

is the abundance of variable stars. In 1907 Miss Leavitt published the results of her examination of Bruce photographs, giving position coördinates and provisional magnitudes at maximum and minimum for 1777 variables. Dur-

FIGURE 21. Distribution of Miss Leavitt's variables in the Large Magellanic Cloud. Dots represent stars of magnitude 15.5 and brighter; circles, stars fainter than 15.5.

ing the current year a number of recent plates of the Large Cloud have been examined by the positive-on-negative method and at the time of writing nearly eight hundred new variables have been added to Miss Leavitt's list of 808. Positions and magnitudes are yet to be determined for the new discoveries; in the course of obtaining this information all

of the sixteen hundred variables will be remeasured, the frequency curve of median magnitudes will be determined as well as a frequency curve of the amplitudes of variation. Meanwhile we show in Figure 21 the distribution of the Leavitt variables throughout the Cloud.

The diagram on which the variables are plotted shows also the general structural features of the Large Magellanic Cloud. The diagonally elongated central part, outlined by dash and dots, is the main axis of the system; the full lines circumscribe the more conspicuously clustered regions; the broken lines indicate semi-clustered regions; and the remainder of the Cloud has been designated "open region." The density of stars varies extremely from the central axis to the open region. For instance, between the sixteenth and seventeenth photographic magnitudes there are approximately seventeen thousand stars per square degree in the "axis" region and only twenty two hundred stars per square degree in the "open" region, both of these numbers having been corrected for superposed stars of our galactic system.

The number of variables and the percentage of stars variable are shown in the following tabulation for the four different kinds of structure. Section I refers to the axis of the Cloud, section II to the heavily clustered parts, section III to the semi-clustered parts, and section IV to the open region.

It is of interest that the variable stars of the sixteenth magnitude and brighter are distinctly less frequent in the clustered regions than elsewhere. This phenomenon holds also in our Galaxy where variables in open clusters are practically non-existent. A recent study of 78 Harvard photographs by Mr. Miller, involving 15,500 stars in and near twelve open clusters, has revealed no certain case of stellar

DISTRIBUTION OF LEAVITT VARIABLES IN THE LARGE MAGELLANIC CLOUD

Photographic magnitude	I		II		III		IV		TOTAL	
	No. of vars.	No. per 100 stars	No. of vars.	No. per 100 stars	No. of vars.	No. per 100 stars	No. of vars.	No. per 100 stars	No. of vars.	No. per 100 stars
]14.1	3	0.9	7	0.1	8	0.4	13	0.8	31	0.4
14.1 —15.0	12	0.7	26	0.3	6	0.2	30	1.2	74	0.4
15.1 —15.5	54	2.9	66	0.9	33	1.0	64	1.9	217	1.4
15.6 —16.0	115	3.5	39	0.4	29	0.7	118	2.1	301	1.3
[16.0	58	0.1	19	0.5	13	0.1	88	0.1	178	0.1

variability. In globular clusters, on the other hand, variable stars are nearly always present, sometimes in great abundance.

e. New Periods for Magellanic Cloud Variables. Since periods have been published for less than five per cent of the variable stars discovered in the Magellanic Clouds, some doubt has arisen as to whether all the variables are periodic and adhere to the period-luminosity relation. The determination of all the periods and light curves must await the accumulation of a large number of photographs, the collection now on hand being insufficient to decide the periodicity and normality of all the variables measured. But recent accumulations of photographs on the Small Cloud have permitted a preliminary test of the generality of Cepheid variability. Miss Mohr and Miss Hoffleit have measured and studied all the known variable stars in a selected area of about one seventh of a square degree. Of the thirty three stars measured, two prove not to be variable at all; of the remaining thirty one variables satisfactory periods and light curves were determined for eighteen. The observations did not suffice to yield the periods for the other thirteen, the

measures being difficult for many stars because of the influence of adjacent images.

From this special survey we conclude that at least sixty per cent of the variables in the Cloud are typical Cepheids adhering to the period-luminosity relation, and we surmise that further observations will show that at least ninety per cent are normal.

As an exhibit of the general uniformity of stellar phenomena among the galaxies, the light curves of these eighteen Cepheid variables in the Small Cloud are illustrated in Figure 22. A comparison of the curves with those for Cepheids of similar period in our own galactic system shows as close an agreement in form as we find among the galactic Cepheids themselves.

Periods have been determined but not yet published for about fifty of the variable stars in the Large Cloud. The resulting period-luminosity relation is apparently identical with that found for the Small Cloud, but the dispersion about the mean curve is slightly larger. This dispersion may be due to the greater thickness of the Cloud, or to observational errors, or possibly to the effect of irregular obscuring nebulosities within the Large Cloud itself. It will be necessary, as soon as plates are available, to determine the period-luminosity relation separately for various parts of the Cloud. The magnitudes of the Cepheid variables may in themselves furnish data on the distribution in the Clouds of the dark nebulosities which otherwise cannot be detected.

The types of research now in progress, especially on the Large Magellanic Cloud, indicate that this nearby galaxy is a potential source of information that will help in the understanding of our own system. Future studies of the Magellanic Clouds will include: (1) an analysis of the globular clusters within the Clouds and a study of the vari-

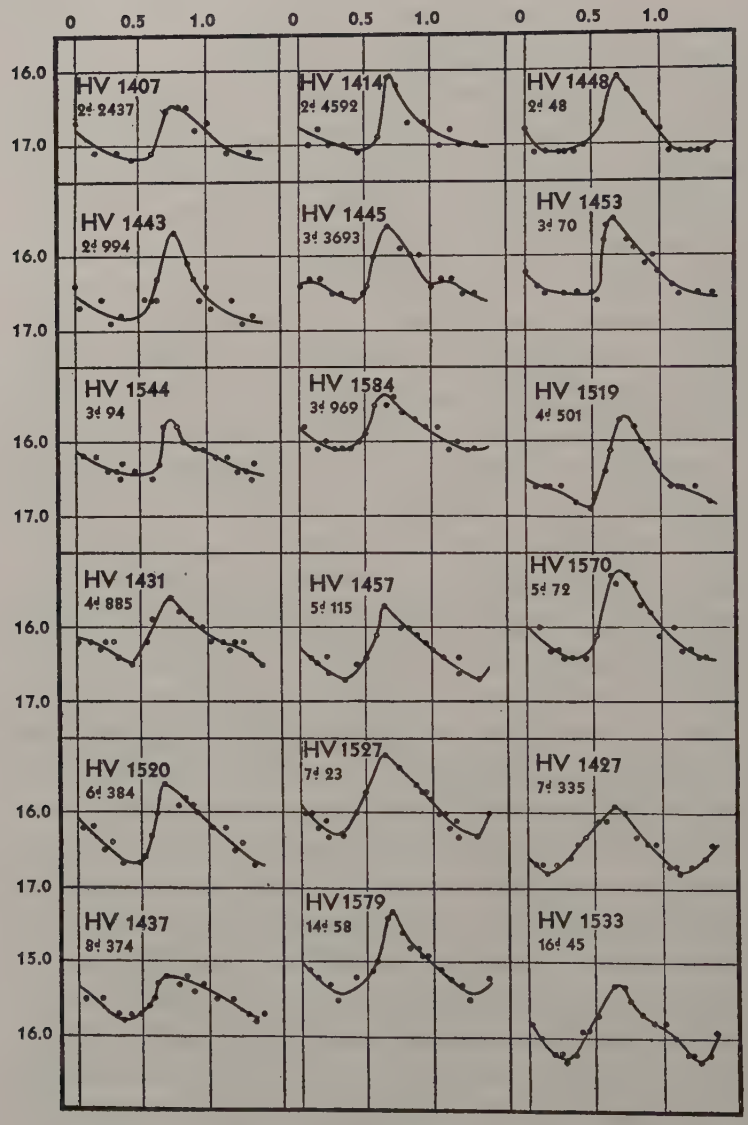

FIGURE 22. Light curves of variables in the Small Magellanic Cloud. Ordinates are photographic magnitudes; abscissae are fractions of the periods. Each point is the mean of five observations.

ables in the clusters; (2) the classification of the spectra of the highly luminous objects, especially in the open clusters; (3) further studies of the velocities in the line of sight, not only of the easily measured gaseous nebulae but also of the stars themselves, since the systematically high radial velocities will help in distinguishing the foreground stars, with their slow and random movements, from the members of the Clouds; (4) the extension of the study of the variable stars to those of the Cepheid type with periods less than one day. All of these researches should be carried forward rapidly with the aid of the 60-inch reflector.

VII

SUPERGALAXIES

THE account of exploratory investigations has thus far passed over six of the eight territories mentioned in the introduction. Within the galactic system proper we traversed in turn the solar neighborhood, the region of lucid stars, the local system, and the Milky Way star clouds. The system of globular star clusters and the two Clouds of Magellan were next considered, and the possibility has been mentioned on an earlier page that these clusters and clouds may be but a part of the supersystem in which the star clouds of the Milky Way stratum are unit galaxies and form the major part of the organization.

If the diameter of the galactic system is actually much in excess of two hundred thousand light years, it may be appropriate to enquire if some of the nearer of the spiral nebulae—such as Messier 33 and the Andromeda Nebula—are not also a part of the supersystem dominated by our Milky Way. But whether or not our own Milky Way system is composed of several units, we are certain that such superorganizations do exist. The Andromeda Nebula has two fainter companions. The Magellanic Clouds may form, as we have said above, a double system. More than fifty binary galaxies are known among the fainter objects of the spiral nebula family, and there are several multiple systems.

The most striking of the supergalaxies is the one we have called Coma-Virgo Cloud A, which lies not far from the north galactic pole and spreads its stream of conspicuous

spiral and spheroidal systems over several hundred square degrees of the sky. On our present scale of distances the Coma-Virgo supergalaxy is approximately ten million light years away. In a study recently completed we have analyzed the distribution, brightness, diameters, types, and orientations not only of the three hundred or so galaxies in Cloud A, but also of the twenty five hundred similar systems that lie far beyond in the same direction. Many of these fainter, more remote galaxies are also grouped into clusters, and it is probable that some of the fainter aggregations lie more than a hundred million light years distant.

Further study of Coma-Virgo Cloud A during the past year has shown its extension across the constellation Virgo into the southern hemisphere. It now appears that this magnificent supersystem, of indefinite boundary, is a long stream of relatively bright external galaxies, but several million light years in extent and thus much larger than our own galactic system. Distinctly shown on the Harvard photographs are at least forty clusters of galaxies, many of which must be more than a million light years in diameter. This does not mean, however, that our own supersystem is uniquely small, either in population or in extent; for the supergalaxies range in diameter from some millions of light years to a few thousand. Stephan's Quintet in Pegasus, for example, appears to be composed of five ordinary spiral and spheroidal galaxies, four of which are essentially in contact and probably extend throughout less space than that occupied by the Milky Way star clouds in Scorpio, Sagittarius, and Ophiuchus.

The long-exposure photographs with the Bruce telescope provide sufficient material for systematic investigations of

the nearer of the supergalaxies. This telescope is not powerful enough to get to the bottom of some of the systems for which we have now photographed only the most luminous galaxies; probably no existing telescope can reach to the under-sized members of these organizations. Studies by Lundmark at Upsala, Hubble at Mount Wilson, Baade at Hamburg, and Miss Ames and the writer at Harvard have shown the considerable dispersion in the actual luminosities and the linear diameters of the members of the supergalactic systems. These diversities in brightness and diameter will make uncertain for years to come our estimates of the distances of the groups. Perhaps the relation between distance and the "red shift" of the spectral lines for external galaxies may eventually give us the most reliable indication of the distances. The whole study of external galaxies is necessarily on a less reliable basis than the studies of globular clusters and the Magellanic Clouds; but the systematic accumulation of observations of magnitudes, motions, diameters, and distribution must eventually provide material adequate for statistical considerations of the structure and distances of supergalaxies.

One of the richest and most distinct of the faint supergalaxies is in the constellation Centaurus. A preliminary survey of the magnitudes of the individual members has been published,[1] and a revision of the magnitudes has since been obtained. As the majority of the individual galaxies in this system are fainter than the seventeenth photographic magnitude, the problem of magnitude standards is serious. The difficulty has been met in a fairly satisfactory manner through establishing a magnitude sequence from counts of faint stars in the Centaurus field; the relation of the number of stars per square degree to a given limiting photographic magni-

[1] Harvard Bulletin 874, 1930.

tude has been determined statistically for all parts of the sky by Seares at Mount Wilson and van Rhijn at Groningen.

It is scarcely appropriate here to give details of the method of measuring the total brightness of the individual galaxies for the Centaurus group; I simply present a tabulation of the frequency of the revised magnitudes, showing how the galaxies grow more numerous as we approach the effective limits of the Harvard plates. Below magnitude

TABLE V

FREQUENCY OF MAGNITUDES IN THE CENTAURUS CLOUD OF GALAXIES

MAGNITUDE	NUMBER	MAGNITUDE	NUMBER
14.65	2	16.45	20
14.85	0	16.65	27
15.05	4	16.85	50
15.25	0	17.05	50
15.45	4	17.25	62
15.65	6	17.45	101
15.85	5	17.65	81
16.05	12	17.85	61
16.25	21	18.05	20

17.5 the survey is probably incomplete, and it fails entirely at the eighteenth magnitude. There is little doubt but that an extension of the survey to the twentieth magnitude would multiply many fold the number of recorded galaxies in the Centaurus supersystem. The distribution of the members appears to indicate that we see here a discoidal system more or less edgewise; in form it is not greatly different from the extended Coma-Virgo Cloud A, and perhaps it is not dissimilar to our own galactic system.

VIII

THE METAGALAXY

TWO systematic surveys of external galaxies, now in progress at Harvard, concern the all-embracing aggregate which we call the metagalactic system. Most of the external systems seem to be scattered more or less at random, both in direction and in distance, except that in low galactic latitudes they are rarely found, presumably because of obstructions by obscuring nebulosities in and on the edges of the Milky Way. A relatively small percentage of the total number of recorded spiral and spheroidal nebulae are assembled into the distinctly delineated supergalaxies.

The less ambitious of the two surveys is a catalogue of the photographic magnitudes of all external galaxies brighter than magnitude 12.9. In the existing general catalogues, such as the N. G. C. and Index lists of Dreyer, the estimated total magnitudes of the nebulae and clusters are only approximate, being referred to uncertain visual standards. Some lists, with higher accuracy in the magnitudes, cover but limited sections of the sky. It is hoped that the new Harvard survey will be more complete and homogeneous than any so far made. Numerous photographs showing the nebulae on a sufficiently small scale for comparison with standard star images are available for the whole sky. Three or more photographs are used for each object. Positions will not be redetermined (they are available from existing catalogues), nor the dimensions measured. The work is simply a photographic magnitude survey. At the time of

writing seventy per cent of the whole sky has been covered, and Miss Ames has measured 675 galaxies brighter than magnitude 12.9. We may assume that this examination of the nearer parts of the Metagalaxy is reaching some five million light years into space, though doubtless many of the intrinsically fainter galaxies within that limit of distance are not recorded, and many of the high luminosity galaxies appear in the catalogue though lying considerably more than five million light years distant.

The second systematic survey in the Metagalaxy reaches to the eighteenth magnitude and fainter and is much more complicated and laborious than the photometric catalogue of objects to magnitude 12.9. The first survey will be completed in a few months, but we shall be fortunate if the second is finished in ten years. It will involve the finding and study of tens of thousands of heretofore uncatalogued objects. The positions, approximate magnitudes, diameters, and classifications of all these faint systems must be completed before the final analysis is made. We may assume as a first approximation that this survey, using long-exposure Bruce photographs which extend to objects five magnitudes and more fainter than those in the catalogue of the nearer systems, will reach to an average distance of fifty million light years. As in the first survey, the limit is indefinite, more distant objects coming in if they are of high luminosity and nearer objects failing to appear if intrinsically faint.

An independent survey of the distribution in brightness and direction of faint galaxies is being made with the Mount Wilson reflectors by Dr. Hubble. The areas covered by him are much smaller than those shown on the Harvard plates, but the magnitude limits are fainter and the total number of nebulae involved is at present of the same order. Hubble's survey is mainly for the northern hemisphere and

the Harvard survey mainly for the southern. These supplementary researches give results in general accordance.

The Harvard eighteenth magnitude survey, as we may call it, has now progressed to the extent shown in Figure 23, which is a map of the whole sky with the completed areas shaded. Each long-exposure Bruce plate covers effectively twenty five square degrees. Approximately one sixth of the whole sky has been examined. About eighteen thousand new systems have been found, for seventy five per cent of which the positions have been determined and for fifty eight per cent classifications made on the Harvard system. In this work low quality photographs have been excluded. The limit to which the satisfactory plates extend is variable, depending on sky conditions and plate sensitivity. Through counts of stars on each photograph we shall be able to determine the approximate limits to which the nebulae are shown.

The number of galaxies per square degree has been counted on all plates in the shaded areas shown in Figure 23, and in Figure 24 the results of this census are given with angular distances from the galactic plane (galactic latitudes) as abscissae and the number of galaxies per square degree as ordinates. Each plotted point refers to a single plate. In low galactic latitudes, though the plates are numerous and of good quality, relatively few galaxies are shown, but for galactic latitudes greater than plus or minus thirty degrees the numbers per square degree average about 14.6 and show great dispersion. We must conclude that the distribution is far from uniform.

The magnitudes of individual galaxies have been estimated for a few fields in the eighteenth magnitude survey and Figure 25 shows the frequency curve for four sample regions. The dissimilarities in these curves are an indication of the

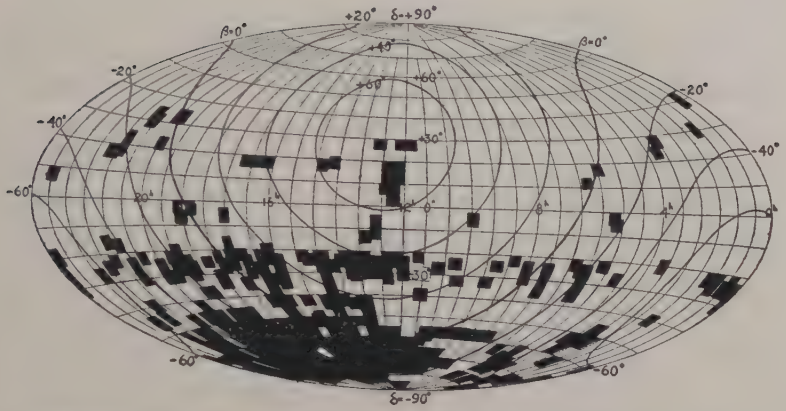

FIGURE 23. Regions of the sky covered by the survey of faint external galaxies. The heavy curved line is the galactic circle. The map is given in the equatorial system of coördinates, but shows also galactic latitude circles.

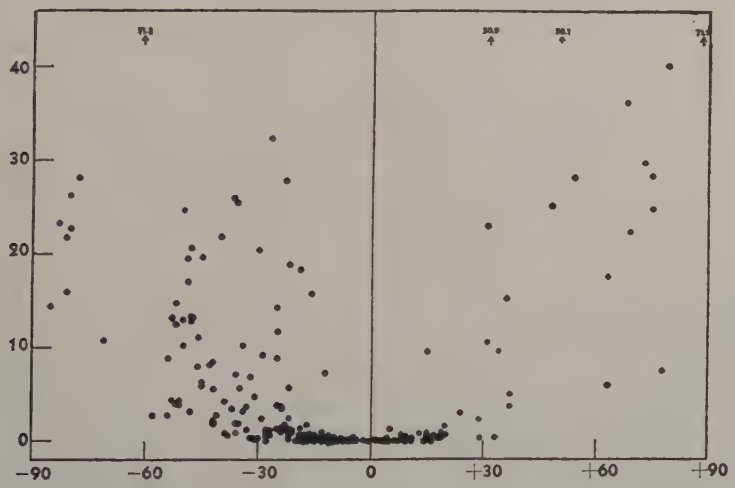

FIGURE 24. Frequency of external galaxies. Ordinates are numbers of galaxies per square degree; abscissae are galactic latitudes.

non-uniform increase in number of galaxies with increasing distance. If the density in space were uniform the number of objects per square degree should increase four times for

every interval of one magnitude (abscissae). Taking the whole sky, we find, in agreement with Hubble, that the increase of numbers with decreasing brightness is approximately of the order of magnitude appropriate to uniform density. But for various large sections of the sky the uniformity criterion fails conspicuously, as shown in Figure 25; for some of the fields, apparently free of supersystems, the number of

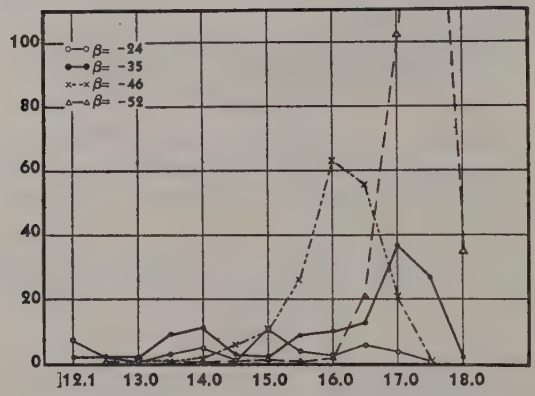

FIGURE 25. Magnitude frequency of external galaxies for four regions. Coördinates are numbers of galaxies and photographic magnitudes.

objects actually falls off with decreasing brightness and for others increases and decreases irregularly.

The current theoretical discussions of the dimensions and finiteness of the space-time world assume a general uniformity in the distribution of galaxies throughout measurable space; hence the interest in extending the census of faint galaxies, and in the measurement of their magnitudes and angular diameters to the faintest possible limits.

In conclusion, two results of our survey of the Metagalaxy merit emphasis. The first is that within the range of existing telescopes we find great irregularity in the distribution

of matter. Some of this irregularity is apparent only, caused by obscuring cosmic clouds in the neighborhood of the Milky Way; but much of it is attributable to the aggregations of galaxies into supersystems and into large indefinite streams.

The second result to be emphasized is that the survey gives no evidence that we have measurably approached the limits of the galaxy-populated universe; on the whole we have no indication that the systems are falling off in number per cubic million light years as we go out from the Sun. On relativistic grounds, the red shift in the spectra of distant galaxies can be taken as an observational indication of an expanding finite universe; but so far as the present census of the Metagalaxy goes, the total number of galaxies and the radius of space may both be infinite.

HARLOW SHAPLEY.

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THREE FRENCH MORALISTS OF THE SEVENTEENTH CENTURY—Three public lectures delivered at the Rice Institute, April 15, 16, and 17, 1930, by HENRI CHAMARD, Professeur de l'Histoire de la Renaissance française à l'Université de Paris.

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II. Pascal 14

III. La Bruyère 31

The Rice Institute Pamphlet is published at Houston, Texas, and is issued in January, April, July, and October. It was entered as second-class matter, April 15, 1915, at the post-office at Houston, Texas, under the Act of August 24, 1912